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THE ECOLOGICAL SIGNIFICANCE OF THE EAGLE CREEK FLORA OF THE COLUMBIA RIVER GORGE

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INTRODUCTION
GEOGRAPHIC LOCATION AND TOPOGRAPHIC FEATURES OF THE COLUMBIA GORGE
GEOLOGIC RELATIONS OF THE EAGLE CREEK FORMATION
THE ECOLOGICAL COMPOSITION OF THE FLORA
PHYSICAL CONDITIONS DURING THE EAGLE CREEK EPOCH
CONCLUSION

INTRODUCTION

During the seasons of 1916 and 1917 considerable collections of fossil plant material were made by the writer in the gorge of the Columbia River, in Oregon and Washington. It has been planned to present a complete report on this material, including a description of new forms, a discussion of the age of the flora, and a consideration of its ecological significance. In view of the possible interruption of this larger task a discussion of the ecological significance of the flora is presented in advance of the fuller report.

Acknowledgment is made to Dr. J H. Bretz, of the University of Chicago, who first directed the writer's attention to this field, and who is responsible for the discovery of one of the most important plant-bearing deposits. I am indebted also to Dr. F. H. Knowlton

for valuable advice and assistance in determining species, and to Dr. H. C. Cowles, of the University of Chicago, for his direction in the interpretation of the ecological data. The work during the season of 1917 was carried on with the aid of a grant from the Research Fund of the American Association for the Advancement of Science, to which organization sincere acknowledgment is due.

GEOGRAPHIC LOCATION AND TOPOGRAPHIC FEATURES OF THE COLUMBIA GORGE

The gorge of the Columbia River is that portion of its valley in the Cascade Range. Its general features are shown in the Mt. Hood sheet of the United States Geological Survey, where the Columbia River forms the boundary between Oregon and Washington. The river has exposed here a section which has a maximum thickness of over 4,000 feet. The basal Eagle Creek formation is displayed at the axis of the range, giving the most complete section just west of the boundary between Multnomah and Hood River counties. The total length of the gorge from Troutdale, Oregon, on the west to The Dalles, Oregon, on the east is about 70 miles. Its width averages about one mile.

The walls of the gorge rise steeply, especially on the Oregon side, where cliffs of basalt rise more than 2,000 feet almost vertically. A number of peaks, some of them representing volcanic cones, lie a short distance back from the edge of the walls. Larch Mountain, 4,045 feet, and Mt. Defiance, 4,960 feet, are conspicuous examples. Numerous small tributary streams flow into the Columbia from each side through canyons which are much shallower than that of the master-stream. As a result each has at or near its mouth a falls or series of falls, the highest being Multnomah Falls, 620 feet high, at the mouth of Multnomah Creek. The sections exposed in the lower stretches of these tributaries add much to our knowledge of the stratigraphy and fossil content of the rocks.

The western two-thirds of the gorge is occupied by the luxuriant forest of Douglas spruce so characteristic of the Pacific coast. Much of the geologic record is hidden by the density of this forest and its undergrowth. The best accessible sections are found where the building of roads and trails has temporarily destroyed the

vegetation cover. Conditions become progressively more arid toward the east, with only a sparse occurrence of pines and oaks at The Dalles.

GEOLOGIC RELATIONS OF THE EAGLE CREEK FORMATION

A recent study of the geology of the Columbia River Gorge by Drs. I. A. Williams and J H. Bretz under the auspices of the Oregon Bureau of Mines has given us a rather complete knowledge of the general geology of this little-known region.[1] As far back as 1873 LeConte recorded the presence of fossil leaf impressions in the volcanic conglomerate at the base of the basalt series.[2] In 1895 Diller secured a small collection of leaves near the mouth of Moffatt Creek which has been described by Knowlton,[3] and four years later Gilbert made a larger collection from a talus block near Cascade Locks, a collection which has never been described. The collections which are the basis of this paper are, however, the first which are sufficiently complete to give any conclusive evidence regarding the age of the Eagle Creek formation.

There are but few cases of such an illuminating record of the history of a mountain range as has been furnished by the Columbia River in its path across the Cascades. Following is the generalized section exposed by the Columbia: gravels and river terraces of recent origin; Herman Creek lava—andesitic basalt; Satsop formation—stream gravels and volcanic ash; Columbia River lava—successive flows of basalt; Eagle Creek formation—volcanic conglomerate, ash, and tuff.

The Eagle Creek formation.—The Eagle Creek formation is exposed along the bottom of the gorge from Warrendale to Viento on the Oregon side with a corresponding distribution on the north side of the river. It is the oldest formation recognized in the region, and is brought to the surface in the axis of the great north-south anticline which is the backbone of this portion of the range. The thickness of the exposed part of the formation varies from 2,700

[1] Ira A. Williams, *Bull. of the Ore. Bureau of Mines and Geol.*, Vol. II, No. 3, 1916; J H. Bretz, unpublished manuscript.

[2] J. LeConte, *Am. Jour. Sci.*, 3d Series, VII, 167–80.

[3] F. H. Knowlton, *Twentieth Ann. Rept. U.S. Geol. Surv.*, pp. 37–64.

feet at Red Bluffs on the Washington side to 500 feet on the Oregon at Bonneville, a condition which appears to be due in part at least to the southward plunge of the fold.

The formation as exposed on Table Mountain and Red Bluffs comprises a series of beds of tuff, ash, and volcanic conglomerate, the conglomerate being most conspicuous near the top. In several of the talus masses of the conglomerate poorly preserved leaf impressions are found, and in both the conglomerate and the tuff silicified wood is common. To the west of Red Bluffs cliffs of conglomerate are conspicuous, and from them have slumped the great masses of rock which have dammed the Columbia River, resulting in its cascades. The base of the formation is reached neither on the Washington nor on the Oregon side.

On the Oregon side the maximum section exposed, 500 feet thick near Bonneville, is a volcanic conglomerate, in most places highly indurated. All the bowlders are of porphyritic basalt, some of them reaching a diameter of 15 feet and averaging from one to three feet in the coarser phases of the formation. The matrix is a fine to coarse volcanic sand. Numerous pockets and lenses of shale and sandstone are a characteristic feature. These are of slight extent both vertically and horizontally, and in many cases contain more or less well-preserved leaf impressions. Silicified logs and carbonized stems and fragments are of common occurrence, representing driftwood deposited with the sediments.

The frequence of volcanic activity during the deposition of the sediments is indicated by the seams of volcanic ash which are seen to overlie some of the soil layers representing old surfaces. A quarter of a mile east of Bonneville occurs what is most probably a contemporary extrusion of basalt, and on Greenleaf Creek the sedimentaries are intruded by basalt. In these situations and elsewhere locally the beds have been contorted and shattered, with the development of slickensided surfaces and contact metamorphism.

The upper surface of the Eagle Creek formation, overlain by basalt flows, is markedly irregular, as first noted by LeConte in the canyon of Tanner Creek.[1] Evidences of intraformational unconformities are numerous and will be discussed below.

[1] *Op. cit.*

Collections of leaf impressions were made in eighteen localities, ranging from the mouth of Moffatt Creek on the Oregon side of the gorge to the foot of the cliffs at Red Bluffs in Washington, six miles distant. These collections, while made up of rather fragmentary material on the whole, include remarkably well-preserved leaves where the matrix is a fine clay. In most situations the leaves were secured just above a layer of carbonaceous shale which represents the old soil line, in the fine sandy or shaley material laid down upon the old surface.

The following description of a locality on the Columbia River Highway shows the typical occurrence of the fossil plants: 850 feet

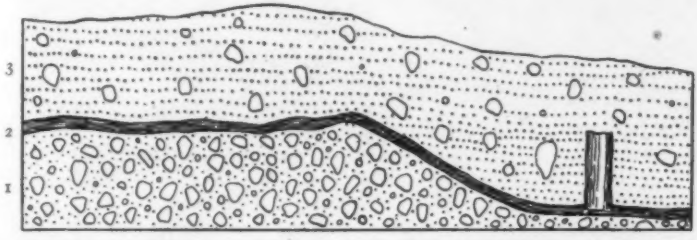

FIG. 1.—Section of the Eagle Creek formation 850 feet west of the Tanner Creek bridge on the Columbia River Highway, showing relations of the soil line and the upright tree.

west of the Tanner Creek bridge on the Columbia River Highway, a bed of cobble conglomerate 20 to 25 feet in thickness is overlain by a carbonaceous seam containing leaves. The general relations are shown by Fig. 1. Here bed 1 is a layer of coarse conglomerate which is overlain by bed 2, a seam of carbonaceous sandy shale from 8 inches to 3 feet in thickness. Overlying bed 2 and inclosing the fossil tree which is rooted in the shale is bed 3, comprising 15 feet of sandstone containing numerous bowlders.

The upper surface of 1 is suggestive of an erosion surface on which several feet of soil 2 accumulated. The upright tree appears to have been growing in a valley cut in 1 during the time of the soil accumulation, and about its roots numerous leaves have been buried and fossilized.[1] The lack of another slope makes the

[1] A microscopical examination of this fossil wood has not yet been made to determine its taxonomic relations.

assumption of a valley uncertain, but in any case the sloping soil line establishes the fact that this old land surface had considerable relief at the time 3 was deposited on it.

The age of the Eagle Creek formation has been imperfectly known, due to the small amount of fossil material previously secured from it. On the basis of these more extensive collections it will be possible to fix the age with reasonable certainty. At present the age may be referred tentatively to Upper Eocene on

FIG. 2.—*Quercus pseudo-lyrata*. One-half natural size

the basis of close resemblances of the flora to that of the Upper Clarno beds of the John Day Basin and related formations in Idaho and California.

THE ECOLOGICAL COMPOSITION OF THE FLORA

It is not the purpose of this paper to describe the composition of the Eagle Creek flora from the taxonomic standpoint. It will be sufficient to note that of some 80 species represented, 75 are angiosperms, of which but 2 are monocotyledons. Following is a provisional list of the genera, with the number of species included in each: *Ginkgo* 1, *Pinus* 1, *Picea* 1, *Smilax* 1, *Cyperacites* 2, *Populus* 3, *Salix* 3, *Hicoria* 2, *Juglans* 1, *Alnus* 1, *Carpinus* 1, *Corylus* 1, *Castanea* 1, *Quercus* 12, *Ulmus* 2, *Planera* 2, *Magnolia* 1,

Laurus 2, *Platanus* 2, *Liquidambar* 3, *Crataegus* 1, *Sterculea* 1, *Rhus* 1, *Ilex* 1, *Acer* 3, and *Fraxinus* 1.

Considering the ecological composition of the flora, the outstanding feature is the presence in it of leaves which represent two distinct ecological types, one xerophytic and the other mesophytic. The former includes several species of oaks, notably *Quercus pseudo-lyrata* (Fig. 2), which is the most abundant species in the flora. The latter comprises most of the remainder of the flora, including a large number of genera and species, of which *Acer bendirei* is represented by the largest number of specimens.

FIG. 3.—*Acer bendirei*. One-half natural size.

Quercus pseudo-lyrata, the most abundant species, is found in twelve of eighteen localities furnishing leaves. Clearly the conditions under which it lived may be said to be widespread. Its leaves have the thickness and coarse epidermis which constitute the morphological expression of a xerophyte. Its modern representatives, *Q. velutina*, *Q. muhlenbergii*, and *Q. marylandica*, have their typical range in xerophytic habitats. It seems entirely probable that *Q. pseudo-lyrata* occupied a similar habitat, an exposed situation with a small amount of moisture.

Associated with this presumably xerophytic species, commonly in the same slab and almost invariably in the same locality, is *Acer bendirei* (Fig. 3), a maple closely related to *A. macrophyllum*, which is an abundant member of the flora now living in the gorge. Even were it not well known that maples are almost exclusively found in well-watered habitats, the mesophytic character of *Acer bendirei* could be ascertained from the thin texture and large size of the fossil leaves. Occurring in fourteen out of eighteen localities it is an abundant species and one which shows moisture requirements widely different from those of *Quercus pseudo-lyrata*.

There is little reason to doubt that these two ecological types represent two distinct habitats from which leaves have become intermingled and fossilized. The abundance of individual oak leaves is adequate evidence that they have not come from scattered relicts of an earlier succession which has been supplanted by one more mesophytic. On the assumption that the xerophytic leaves are xeromorphs and owe their structure to a physiologically dry habitat such as a bog, a twofold habitat would still be required, for such xeromorphic forms would not be included in the same association with typical mesophytes like *Acer*, *Ulmus*, and *Platanus*. Further, the typical xeromorphic leaf is entire-margined, while *Quercus pseudo-lyrata* has conspicuous lobes and sinuses. On the basis then of two habitats contributing leaves, we may consider the general type of topography required by the plant evidence.

In many parts of the United States today the uplands are occupied by a xerophytic oak association due to the exposure of such a habitat to the sun and the wind, and the consequent high rate of evaporation. Where such an upland is dissected by valleys, especially by those with rather deep and narrow dimensions, these more protected situations may furnish conditions favorable for the development of a typical mesophytic flora. We may have, then, as a common occurrence, a xerophytic upland association with mesophytic tracts along the streams. Leaves from the upland trees are transported widely, due to exposure to winds, and may be carried down into the valleys and mixed with those of the mesophytes growing there. Such situations are so common today that there is little danger in assuming that they were common during the Eagle Creek epoch, though the geological evidence of such topography should be forthcoming if such were the case. On the basis of the plants, however, it is reasonable to assume the existence of this upland habitat, supporting an oak forest, and occasional valleys occupied by mesophytic maples, elms, and other species.

The mixture of the xerophytic and mesophytic types of leaves may thus be explained on the basis that the former were brought in from above and mixed with the mesophytes in the valley deposits. Aside from the exposed situation of the uplands, which would

favor the wide scattering of the leaves which fell upon it, there is the added feature that the thick xerophytic leaves alone would be strong enough to undergo transportation without being destroyed. Surely we must assume that the perfect specimens of maple, sycamore, and other broad thin leaves were not transported far from the spot where they first fell. Further, the large number of mesophytic species associated with the dominant maple and elm leaves indicates that the deposits containing them were laid down in the valley where they grew.

The evidence of the plant fossils thus may be explained on the basis of a twofold habitat such as would be furnished by an upland region traversed by valleys. Whether or not this hypothesis is supported by the geological evidence may be determined by a consideration of the physical conditions which existed during the Eagle Creek epoch.

PHYSICAL CONDITIONS DURING THE EAGLE CREEK EPOCH

The Eagle Creek formation is made up entirely of volcanic materials. In the lower part, as exposed at Red Bluffs, beds of tuff and ash are most conspicuous; above, the activity of streams is evidenced by the predominance of conglomerate. Thus it is clear that early in the epoch vulcanism was the dominant process but that toward the close the streams were able to carry and assort the volcanic material as fast as it was ejected, as well as erode the lava flows bordering the craters. This sedimentary phase is the only one represented on the Oregon side of the gorge and is the source of practically all of the fossil plants.

There are several conspicuous features, applying especially to the conglomeratic phase, which require analysis. In the first place there is a predominance of coarse material—rounded bowlders ranging up to 15 feet in diameter and averaging from 1 to 3 feet. The textural range is high in any outcrop, large bowlders mingled with small, all bound together by a matrix which varies from coarse gravel to fine mud, but is commonly sandy in texture. The abundance of large bowlders and the almost entire lack of assortment point to the deposition of these sediments by streams which had high velocity.

In the second place the stratification where present is of the lens and pocket type rather than in horizontal layers. This applies to coarse as well as fine materials, but is especially conspicuous in the case of the latter. Nearly all of the sandy and shaley phases occur in the form of lenses or pockets having a horizontal distribution of a few tens of feet and a thickness, with few exceptions, of not more than 15 to 20 feet. This is suggestive of fluctuating conditions of deposition, due either to a variation in the kind of materials available for transportation by the streams, to a variation in the volume of the streams, or to a wandering of the streams over the depositing portions of their courses.

Both of these features suggest that the sedimentation was of the bajada type, like that on the flanks of the Sierras.[1] If the Eagle Creek conglomerates were laid down as alluvial fan deposits, it is clear from their thickness that they were deposited on the flanks of a range of considerable height. This brings to consideration a third feature, that of the variation of thickness in the area. At no place is the base of the formation reached, but the observed thickness at Red Bluffs is 2,700 feet, while south of the river its exposed part is little more than 500 feet thick. This variation may be explained in two ways: first, that it is due to the southward plunge of the Cascade anticline, which would carry the top of the formation down to within 500 feet of river level (assuming a dip of about 10°); and, second, that it is related to the position of the high land which was the source of the sediments, the deposits on the immediate flanks being thickest, with a thinning outward as the distance from the source increased. Assuming that the Eagle Creek conglomerates were laid down on the flanks of an east-west range, as shown by Fig. 4, there should be other evidences of the proximity of the thicker section to the flanks of the range. It is probable that this range contained the vents from which the pyroclastics were ejected. We should therefore expect to find ash and tuff more conspicuous in that portion of the bajada nearest the range. At Red Bluffs, as has been stated; ash and tuff in alternating layers comprise most of the visible portion of the Eagle Creek formation, except near the top, where conglomerate is more

[1] A. C. Trowbridge, *Jour. Geol.*, XIX, 707–47.

conspicuous. On the Oregon side, farther away from the supposed range, the amount of pyroclastic material is relatively inconspicuous, as might be expected at a distance of 6 to 8 miles from the range.

It may be suggested that the 500-foot section of conglomerate on the Oregon side of the gorge represents the upper conglomeratic portion of the Red Bluffs section, and that the ashy and tuffaceous lower portion lies below. Surely the southward dip of the overlying basalt makes this explanation of the variation in thickness plausible. On the other hand, it appears reasonable to suppose that the 500 feet exposed on the Oregon side represents more than

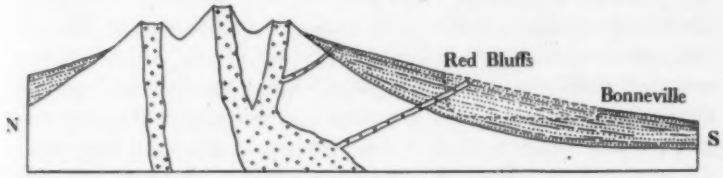

FIG. 4.—Showing the possible relations of the Eagle Creek formation on the flanks of a volcanic peak or range. The dashed line indicates the present position of the Gorge of the Columbia River in cross section.

the upper 500 feet of the Red Bluffs section. There are more intrusions in the latter, as might be expected at a point nearer the mountain range. And the paucity of plant remains in the conglomerates of Red Bluffs also has significance when it is realized that the proximity to volcanoes would probably be unsuitable for the growth of vegetation. It is of course possible that were the upper part of the Eagle Creek section readily accessible for study, plant-bearing lenses might be found in abundance there; but in all of the talus material examined at the foot of the cliffs only two masses contained leaf impressions, and these but few. The variation in thickness of the formation from north to south may then be due to a greater or less extent to the distance from the range constituting the source of the sediments.

In summary, the lithological characters of the Eagle Creek formation—its coarseness, lack of assortment, and lens and pocket stratification—point to the origin of the conglomeratic layers as a

bajada deposit on the flanks of a mountain range lying to the north, a range whose volcanoes threw out the great volume of pyroclastic material, and which later were perhaps the sources of the basalt flows. The variations in thickness from north to south are in accord with this geographic relation, for the formation appears to thin toward the south.

We may outline the physical history of the Eagle Creek formation as follows: To the north of the gorge, an east-west range of mountains contained volcanoes which were active throughout the epoch, though probably less active toward its close. Large amounts of ash and tuff were thrown out, covering the flanks of this range to a depth of more than 2,000 feet. During intervals of volcanic inactivity streams assorted this material, producing the beds of volcanic conglomerate. Toward the close of the epoch streams assumed dominance and transported large amounts of volcanic débris out from the axis of the range, depositing it as far away as the present south side of the gorge but in progressively lesser amounts. Thin layers of ash in the sections on the south side indicate that a small amount of pyroclastic material was carried there directly from the vents. The dominance of clastic sediments indicates, however, the relatively greater importance of stream deposition here, and the presence of conditions suitable for the development of plant life.

Some idea of the topographic relations of such a bajada deposit on the flanks of a high range may be gained from the description of similar deposits of the Sierras.[1] Here the alluvial plain is traversed by numerous streams flowing out at right angles from the range, streams which on losing their gradient drop their loads of coarse débris. This piles up until the deposit is considerably higher than the areas on either side, whereupon the streams are shifted laterally into the lower areas and deposition is continued there. For the purposes of this discussion it is sufficient to note that the surface of the bajada in the Sierras is characterized by numerous rather steep-sided ridges which result from stream deposition, and that most of the vegetation is found in the valley-shaped lowlands between.

[1] A. C. Trowbridge, *op. cit.*

We may now turn to the plant record to see how the biological evidence corresponds with the geological. It will be recalled that there are two distinct ecological types represented in the flora, the one composed of fewer species but including the larger number of individual leaves, indicating an exposed habitat; the other composed of many species, indicating a protected habitat. Clearly the xerophytic association would have found its place on the ridges, the mesophytic association in the depressions such as are furnished by the bajada topography. Leaves from the oaks on the ridges might easily be blown or washed into the depressions below, there to be mixed and buried with the leaves of the mesophytic maples and elms growing along the streams. The bajada topography fits well with the ecological requirements of two habitats, one exposed and xerophytic, the other protected and mesophytic.

However well these ecological requirements are fulfilled by the bajada topography, there should be some actual record of the latter if it existed during the Eagle Creek epoch. During the first season's work no such evidence was discovered. The requirements of the plants were unsatisfied until a second visit to the gorge, during which several situations were found where the topography developed during the epoch showed distinct relief. Along the Columbia River Highway cut west of the Tanner Creek bridge, two places were noted where a soil line slopes sharply into a depression. In one of these (see Fig. 1) the soil line slopes down at an angle of 22° and the depression below contains the upright stump of a large tree. Similar situations on Moffatt and Eagle creeks were observed. In the latter the material deposited over the leaf-bearing bed is clearly a valley fill, as shown by the horizontal bedding of the gravelly layers in the sandstone. Further, as previously noted, the upper surface of the formation has marked relief. Clearly the old surfaces within and at the top of the formation show that there were ridges and depressions such as the evidence of the plants demands and such as would have been present in a bajada deposit.

A consideration of the climatic conditions indicated by the plants is next in order. The numerical predominance of the xerophytic form, *Quercus pseudo-lyrata*, and its occurrence in nearly all the deposits where large collections were made indicate

that the upland conditions were such as to support an oak forest. Today the uplands, in the western part of the gorge at least, are occupied by the more mesophytic Douglas spruce (*Pseudo-tsuga*). Comparing the upland plant associations of the Eagle Creek epoch and the present, we are justified in concluding that the climate was more arid then than it is now. Looking to the mesophytic valley association of the Eagle Creek flora, the presence in it of such moisture-requiring forms as *Acer bendirei*, *Ulmus speciosa*, and others indicates that in the depressions the air was moist. This moisture was no doubt contributed in large part by the streams occupying the valleys, but the very presence of so mesophytic an association indicates that even semiaridity did not exist anywhere in the region. Rather the moisture conditions were like those at present existing in the eastern part of the Great Plains, where the mesophytes are restricted to the stream borders along the valleys because the soil there is moist. Such at least is a reasonable conjecture. The cause of the greater aridity in Eocene times than at present is not known. Presumably a mountain range to the west may have cut off the moisture-bearing winds, thus reducing the amount of rainfall, though there is no direct evidence for supposing that such a range existed.

Concerning the temperature, the presence of such tropical or subtropical forms as *Smilax*, *Sterculea*, and *Liquidambar* suggests that the climate was warmer than that in the region today. The dominance of such temperate types as *Quercus*, *Acer*, *Ulmus*, and others puts the evidence in favor of a climate which was cooling, with the resultant invasion of the tropical flora by these temperate species. Apparently the climate, while somewhat warmer, was approaching the temperature conditions of the region today.

The flora of the Eagle Creek formation gives valuable suggestions as to the length of time involved in the epoch. From a purely physical standpoint, the great thicknesses of ash, tuff, and conglomerate might have been piled up in a comparatively short time, perhaps measured in scores of years rather than in units of a larger denomination. Turning, however, to the evidence of the plants, it may readily be shown that the time required is much greater. The number of years necessary for the development of a

climax forest of a mesophytic sort is estimated to be from one to two hundred years. This is on the basis of there being no soil at the outset, and of its development through the agencies of plants and weathering. It also assumes a soil favorable for the reception of plants. In the case of the soil furnished by the Eagle Creek rocks, there was a distinct time advantage due to the fact that they were not consolidated and therefore offered an immediate foothold for rooted plants. On the other hand the chemical composition of this sediment was probably quite unsuitable for the growth of most higher plants, certainly for the growth of mesophytes. The latter require a humus content which was entirely lacking in the original volcanic materials. Further, due to its basic composition, this may be supposed to have been quite unfavorable for the development of such seedlings as germinated in it. Experimental evidence has shown that of seeds planted in pulverized Eagle Creek rock from several localities, only those of oaks (xerophytes) developed successfully. The experiments were not satisfactorily completed, and it is not known whether the oak seedlings would have continued to develop in this soil. Observational evidence from regions recently covered by volcanic ash indicate that a number of years may elapse before the return of the higher plants. It is not unreasonable therefore to assume that the full one to two hundred years would have been required for the development of a climax mesophytic forest on the volcanic débris-strewn surface during Eagle Creek times.

While it is not possible to correlate the various horizons which contain plant remains in widely separated parts of the area, due to their limited horizontal extent, it is possible to determine, on the basis of relative elevation, that there are at least ten distinct horizons represented. Each of these contains leaves of the climax forest which, as we have seen, would require from one to two centuries for its development. The total length of time involved in the growth of the ten plant horizons may thus be placed at from one to two thousand years. And when it is realized that there must be numerous other plant-bearing horizons which have not been uncovered, the length of the epoch as inferred from plant growth may be greatly extended.

CONCLUSION

Plants may, then, with a degree of caution, be used, not only to show the character of past climate, but they may also be called upon to indicate the length of time involved in a given epoch, and the general character of the topography.

In the case of the Eagle Creek flora the climate appears to have been somewhat warmer and drier than at present. The length of the epoch is to be placed at thousands rather than at scores of years. The evidence of the dominant species of plants points to the probable existence of a twofold habitat, one xerophytic and the other mesophytic. An upland cut by valley-like depressions furnishes the conditions which are thus required by the plants and at the same time fits in equally well with the strictly geological characteristics of the Eagle Creek formation.

ON OÖLITES AND SPHERULITES[1]

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COLLOID-CHEMICAL INTERPRETATION OF ORIGIN OF OÖLITES

Schade's work.—The most important contribution toward a satisfactory interpretation of the origin of oölites and related structures was made by a member of the medical faculty of the University of Kiel, H. Schade, in 1909 and 1910, in his papers on the origin of urinary calculi and on the formation of concrements.[2] In these he demonstrated experimentally that concretionary bodies form when a substance passes from the state of an emulsion colloid (or "emulsoid") to that of a solid, and that if the change leads to the crystalline state the resulting structure is radial if the substance is pure; if, however, other substances, colloid or crystalloid, are precipitated along with it a concentric structure is developed. Corresponding with this law, natural holesterin gallstones, when 80 to 90 per cent pure, show a radial crystalline structure, while gallstones containing 25 per cent or less holesterin exhibit perfect concentric lamination.

Observations on iron chloride.—A substance which lends itself well to a demonstration of the process involved, because it requires no special preparation, is the commercial hydrated iron chloride. A

[1] A rock is called "oölitic," or an "oölite," if it contains or consists of small grains or units of dominantly concentric structure. A rock is called "spherulitic" (but not a spherulite) if it contains or consists of small grains or units of dominantly radial crystalline structure. An individual grain of a spherulitic rock is called a "spherulite." For an individual grain of an oölite the term "ovulite" might be used, which appears to be preferable to Kalkowsky's "oöid" not only for symmetry's sake. In this paper the term "spherite" will be used for all grains of the same origin irrespective of their structure.

[2] Heinrich Schade, "Zur Entstehung der Harnsteine und ähnlicher konzentrisch geschichteter Steine organischen und anorganischen Ursprungs," *Zeitschr. für Chemie und Industrie der Kolloide*, IV (1909), 175–80; "Ueber Konkrementbildungen beim Vorgang der tropfigen Entmischung von Emulsionskolloiden," *Kolloidchemische Beihefte*, I (1910), 375–90.

concentrated solution of this salt, as was noted accidentally, exhibits all the characteristics of an emulsion colloid; for instance, a noticeable change of viscosity with change in temperature, stability in the presence of salts with polyvalent ions, etc. When dried at ordinary room temperatures, large spherocrystals are formed, perfectly spherical in shape when formed freely suspended in the heavy liquid, hemispherical in shape when formed in contact with the walls of the vessel or with the surface of the liquid. So far I did not succeed in preparing thin sections of these bodies, owing to the low melting-point of the salt (42° C.). In very thin layers, however, spread out on a slide, the growth is seen to take place in one plane only, yielding layers thin enough for optical study. This, combined with a macroscopic observation of the bases of the hemispheres, gave the following results:

Spherites formed relatively rapidly during normal evaporation appeared structureless on cross-section with the center distinctly darker but not sharply separated from the rest. In other cases there was a sharply defined light center, and sometimes an outer lighter layer, distinct from the rest. Some spherites seemed to have formed through the union of several macroscopic drops, judging from an indistinct pattern shown in cross-section. When formed on a slide, growing in one plane only, they always exhibited a radial crystalline structure, the individual fibers being visible under the microscope. Superimposed on this radial structure there appeared in some of the spherites, on the same slide with the others, concentric lines outlining separate crystalline layers, which, however, all consisted of the same material.

Spherites formed during extremely slow evaporation (due to a crust formed on the liquid) showed a concentric structure of delicate layers of different color, especially in their outer part, representing in every respect true oölites. In several cases ten and more layers were counted in a radius of 2 mm.

These experiments illustrate well the principles of Schade: (1) the spherical shape of spherites is due to the tendency of the droplets, forming during the separation of the dispersed phase of an emulsoid, to coalesce;[1] (2) the difference between spherites of

[1] The solid crust which, in some experiments, formed on the viscous liquid containing the growing spherites was, in every case, ruptured upon further loss of water,

radial and concentric structure depends on the amount of other substance thrown out simultaneously with, and mechanically enmeshed in, the growing structure.

Ordinary concretions seem to differ only in size and, in many cases, in an excess of mechanically enmeshed materials. That these principles underlie the formation of most, if not all, sedimentary oölites, spherulites, and concretions is rendered probable by the fact that almost all substances which are known in one of these forms are also known in the others and are the same that are known to occur extensively in nature in the colloidal state. A brief review will emphasize this relation.

Review of natural oölites.—1. Silica: Des Cloizeaux found spherulites of clear silica in a jelly-like paste.[2] Spherulitic hyalite was observed by Jimbo from the Etchu province of Japan,[3] and similar hyalites with concentric structure from hot springs in the Ugo province were described by Takimoto.[4] Silica plays the rôle of the "binding" colloid in most pisolites and is an important constituent of most iron hydroxide oölites. Siliceous concretions are of wide occurrence. Silicic acid is the standard inorganic emulsoid sol of the laboratories.

2. Water: Among the hailstones we find all transitions between typical spherulites and spherites of concentric structure.[5] That

and from the opening extensive *botryoidal surfaces* grew up, leaving cavities underneath the crust. Iron chloride, therefore, offers a complete analogy to all the common forms of natural gels, especially such as have a tendency to grow crystalline *in statu nascendi*, as, for instance, chalcedony. Cf. F. Cornu and H. Leitmeier, "Ueber, analoge Beziehungen zwischen den Mineralien der Opal-, Chalcedon-, der Stilpnosiderit-, Haematit- und Psilomelanreihe," *Zeitschr. für Chemie und Industrie der Kolloide*, IV (1909), 285–90.

[2] F. Roth, *Allgemeine und chemische Geologie*, I (1897), 591, Anm.

[3] K. Jimbo, "The Siliceous Oölite of Tateyama, Etchu Province," *Beitr. z. Min. Japans, Tokio*, 1905, pp. 11–75 (quoted from abstract in *Zeitschr. für Chemie und Industrie der Kolloide*, IV [1909], 287).

[4] T. Takimoto, "The Siliceous Oölite of Sankyo, Ugo Province," *Beitr. z. Min. Japans*, 2 (1906), 60–61 (quoted from *Neues Jahrb. für Min.*, etc., I [1907] 197).

[5] According to Schade the coarse layers overlapping onion fashion, frequently met with in hailstones, are not equivalent to the exceedingly delicate lamination of true oölites, but are due to plastic deformation under external pressure. See Schade, *Kolloidchemische Beihefte*, I (1910), 388; "Ueber die Koëxistenz des kristallinischen und kolloiden Zustandes," *op. cit.*, pp. 389 ff.

water vapor in the atmosphere frequently has the properties of an emulsion colloid is well known.

3. Hydroxides: The hydroxides of iron, manganese, and aluminum occur in all three forms with the exception of the last named, which is, as far as I know, not found in spherulitic or analogous structures. Aluminum hydroxide has, however, little chance to occur in the pure state. "Meta-"hydroxides in concentrated solution are known to be in the emulsoid state[1] and are widely distributed in that form in nature.

4. Phosphates: Phosphatic oölites are common in our western phosphate beds. Concretions are widespread and some show radial crystalline structure. The colloid origin of certain phosphates has long been recognized.[2] Because of the emulsoid character of their sols the phosphates are classed with the "gelatinous salts."[1]

5. Barite: Oölites consisting largely of barite with small amounts of gypsum and selenite were described by Wuestner[3] and Moore[4] from oil wells in Hardin County, Texas. They are of special interest because at least some of them undoubtedly formed in the wells after they were equipped, since they are found inside the tubing in sizes which could never have passed through the small mesh of the screen.[5] As the oil in the well has a temperature of 125° F. and contains free sulphuric acid, they offer a good example of an unquestionable case of an inorganic production of oölites. Fortunately some of these oölites, as shown on the micrographs of Wuestner's paper, Figs. 2–4, exhibit the same pattern of tubes radiating from the center which is so frequently seen in sections of sedimentary calcareous oölites[6] and which Kalkowsky, in his

[1] Ostwald Wolfgang, *Handbook of Colloid-Chemistry*, translated by Martin H. Fischer (Philadelphia, 1915), p. 51.

[2] A. F. Rogers, "A Review of the Amorphous Minerals," *Jour. Geol.*, XXV (1917), 530–33.

[3] H. Wuestner, "Pisolitic Barite," *Jour. Cincinnati Soc. Nat. Hist.*, XX (1906), 245–50, 4 figs.

[4] E. S. Moore, "Oölitic and Pisolitic Barite from the Saratoga Oil Field, Texas," *Bull. Geol. Soc. America*, XXV (1914), 77–79.

[5] E. S. Moore, "Additional note on 'The Oölitic and Pisolitic Barite from the Saratoga Oil Field, Texas,'" *Science*, N.S., XLVI (1917), 342.

[6] For instance, in the oölites of the St. Louis limestone. They are also seen in two sections of bladderstones in the author's possession.

beautifully illustrated paper on the oölites of the Buntsandstein of northern Germany,[1] used as arguments in favor of an organic origin. The formation of the (unstable) barium sulphate sol in this case is possibly analogous to its formation in glycerin, as described by Recoura.[2] Barite concretions are locally found in shales.[3]

6. Calcium carbonate: In the sedimentary oölites we have all transitions from spherulitic to concentric structure. Perfect spheres of calcium carbonate, measuring 1 cm. and more in diameter, with excellent radial crystalline structure were described by the author from Miocene limestones of the Rhine valley.[4] Calcareous concretions are very common. In Drew's experiments, in which he proved the precipitation of calcium carbonate from sea water by *Bacterium calcis*, the first turbidity appearing in his solutions was caused by particles of such fine grain that they could be centrifuged only with difficulty. This suggests a colloid state. In the same experiments small spherulites were formed.[5] Vaughan allowed bottles containing Bahaman shoal-water muds strained through bolting cloth of fine mesh to stand over three months, after which he found in them numerous oölite grains which had grown to such sizes as to preclude their passing through the mesh of the bolting cloth.[6] The gel of calcium carbonate resulting from the precipitation of calcium carbonate from a solution of water-soluble calcium salts and its tendency to form spherulites have long been known. Owing to the elaborate studies of Buetschli, calcium carbonate is perhaps the best known of the "gelatinous salts."[7]

[1] E. Kalkowsky, "Oölith und Stromatolith im norddeutschen Buntsandstein," *Monatsber. d. Deutsch. geol. Ges.*, LX, Part I (1908), 68–125, especially p. 122.

[2] M. A. Recoura, "Sur le sulfate de baryum colloïdal," *Compt. Rend.*, CXLVI (1908), 1274–76.

[3] See, for instance, J. P. Rowe, "Nodular Barite and Selenite Crystals of Montana," *Am. Geologist*, XXXIII (1904), 198–99; for a case in which the primary origin of these concretions is obvious see W. H. Bucher, "Beitrag zur geologischen und palaeontologischen Kenntnis des jüngeren Tertiärs der Rheinpfalz," *Geognostische Jahreshefte*, XXVI (1913), 31.

[4] Bucher, *op. cit.*, p. 80.

[5] G. H. Drew, "On the Precipitation of Calcium Carbonate in the Sea by Marine Bacteria," etc., *Carnegie Publication No. 182* (Washington, 1914), pp. 30–31.

[6] T. W. Vaughan, "Preliminary Remarks on the Geology of the Bahamas," etc. *Carnegie Publication No. 182* (Washington, 1914), pp. 51–53.

[7] Q. Buetschli, *Abh. Goettinger Akad.*, N.S., IV, 1908.

7. Siderite: Siderite is occasionally found in spherulitic form in cavities of basalt (spherosiderite).[1] Dana, Naumann-Zirkel, and others mention the existence of oölitic siderite. The only description of such an occurrence that has come to my attention is that of a specimen described by Dewalque from the Belgian coal measures.[2] Sideritic concretions ("clay ironstone") are commonly associated with caustobioliths.

This association is significant, since a colloid form of siderite was described by Van Bemmelen from the upland bogs of the Dutch province Drenthe, where it is found in the form of concretionary masses in irregular distribution in the peat.[3]

North of Preston, in Bath County, Kentucky, the Devonian limestone, which normally is dolomitic and more or less cherty, is partly replaced by a siderite. A specimen of the ore, presented to me by Dr. A. M. Miller, shows numerous small oölitic grains (0.5 mm. in diameter) of a light green silicate, uniformly distributed through the dark brown rock, which, under the microscope, exhibit a delicate concentric structure, rather indistinct in some grains (Figs. 1 and 2). The surrounding groundmass offers the usual appearance of interlocking siderite crystals. But at the contact with the oölites the siderite crystals show the sharp outlines of perfect rhombohedrons extending into the body of the oölites without disturbing their concentric structure. In this remarkable case the silicate oölites apparently formed in free suspension in a matrix which must have been an amorphous mud or a gel of iron carbonate, which later crystallized out before the oölites had lost their gelatinous character.

The necessary reducing conditions under which this local deposit originated within the coral-bearing dolomites of the Onondaga Sea may have existed in a depression on the bottom of the shallow sea in which the water lay stagnant,[4] or in a lagoon, which would not seem improbable if the assumption of a large island or peninsula

[1] As, for instance, at Steinheim, Hessia, where the author had occasion to observe and collect it.

[2] G. Dewalque, *Ann. d. l. Soc. géol. d. Belg.*, XV, Bulletin (1888), p. lxxx.

[3] J. M. Van Bemmelen, *Zeitschr. für anorg. Chemie*, XXII (1899), 313.

[4] See, for instance, J. Murray and J. Hjort, *The Depths of the Ocean* (London, 1912), p. 257.

in the Onondaga Sea, just to the northwest of this locality, is correct.[1]

These observations render it probable that other sedimentary siderite deposits, especially such as are closely associated with

FIG. 1.—Photomicrograph of oölitic grains of a light green silicate in a groundmass of siderite and (secondary) iron hydroxide, forming a local facies of the Onondaga limestone near Preston, Bath County, Kentucky. Note the free edges of the siderite crystals extending into the oölitic grains, cutting through their structure, mostly without disturbing it; also the discordance between outline and structure of the grain near the lower margin. (The longest diameter of this grain measures 0.7 mm.)

caustobioliths (black shales, coal, etc.), first separated out in the colloidal form and subsequently assumed crystalline character.

[1] C. R. Stauffer, "The Middle Devonian of Ohio," *Geol. Surv. of Ohio*, 4th Ser., Bulletin 10, 1909, Pl. 14; C. Schuchert, *A Text-Book of Geology*, Part II (New York, 1915), Pl. 15B; C. Butts, "Geology and Mineral Resources of Jefferson County, Kentucky," *Kentucky Geol. Surv.*, Ser. 4, Vol. III, Part II, Fig. 3.

8. Silicates: Some hydrous iron silicates, as, for instance, the greenalite of the Lake Superior region, and hydrous iron-aluminum silicates, as, for instance, the chamosite of the Jurassic "Minette" ores of Europe and the similar silicates of our Silurian ores, occur extensively in the oölitic form. They show all characteristics of original gels. In the case of greenalite the tendency to aggregate into numerous spherical grains was evident in the experiment.[1] Distinct oölitic structure is also seen in a specimen of fire clay, from the base of the Pottsville from an unknown locality in eastern Kentucky, which was presented to me by Dr. A. M. Miller. A similar occurrence was described by Dr. W. A. Tarr at the last meeting of the Geological Society of America. For the present the question must remain undecided if in these oölitic clays the binding substance is silica or a silicate.[2]

9. Iron disulphide: Only one case of an oölite has come to my attention in the formation of which pyrite seems to have had an independent part; that is, in which it is more than merely a mechanically enmeshed constituent or of secondary origin. In the upper Lias of Northwestern Germany there occur beds which consist partly of massive pyrite cementing the shells of belemnites and ammonites, and partly of nearly black limestone rich in pyrite, the two phases grading one into the other. In the black limestones oölites are found of a deep black color, measuring 0.5–3.0 mm. in diameter, and consisting of sharply defined alternating layers ("shells") of yellow pyrite and black calcium carbonate (soluble in cold HCl with effervescence).[3] Spherical nodules of pyrite with a fibrous radiated structure are not uncommonly found in shales,[4] and ordinary concretions are common. Recently a

[1] C. R. Van Hise and C. K. Leith, "The Geology of the Lake Superior Region," *U.S. Geol. Surv. Mon.*, LII (1911), 522–25.

[2] Cf. Rogers, *op. cit.*, p. 535 ("imperfect pisolitic structure" in a clay consisting largely of the amorphous equivalent of crystalline kaolinite). A fire-clay containing small rounded bodies which are nearly pure alumina was described by Greaves-Walker in *Trans. Amer. Ceram. Soc.*, VIII, 297; quoted from Ries, "Clays" (New York, 1914), 52–53.

[3] T. Brandes, "Die faziellen Verhätnisse des Lias zwischen Harz und Egge Gebirge," etc., *N. Jahrb. für Min.*, etc., Beil. Bd., XXXIV (1912), 391.

[4] For a good example see, for instance, E. M. Nörregaard, *Meddelelser fra Dansk Geol. Fören*, XI (1906), 105.

black amorphous form of iron disulphide was described by Doss, who called it Melnikowite.[1] It is found in the form of small lenses and occasional thin incrustations of Pelecypod shells in gray clays of Miocene age and especially in solid layers of a pyritic sandstone. These consist of a mixture of pyrite and of this amorphous iron

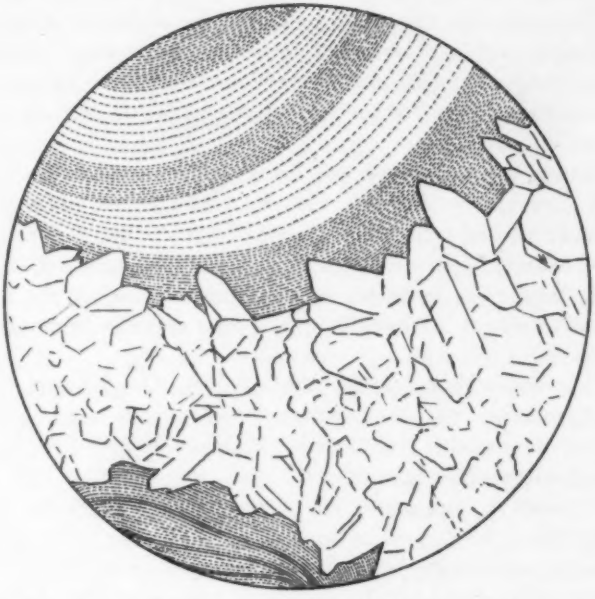

FIG. 2.—Sketch showing the free ends of the siderite crystals extending into oölitic grains. From the same slide as the preceding figure. The large, nearly perfect crystal at the contact in the lower right-hand quadrant measures 0.08 mm. in length.

NOTE.—Owing to the extreme softness of the silicate, A. C. McFarlan, one of my students, who prepared this and numerous other slides for me, was unable to avoid scratches on the oölitic grains. I am also under obligations to P. Scherrer for valuable assistance in the making of microphotographs.

disulphide and contain abundant sand grains which, however, are everywhere seen to be suspended in the groundmass of disulphide. This must, obviously, have been in the state of an amorphous

[1] B. Doss, "Ueber die Natur und Zusammensetzung des in miocaenen Tonen des Gouv. Samara auftretenden Schwefeleisens," *N. Jahrb. für Min.*, etc., Beil. Bd., XXXIII (1912), 662–713.

precipitate or of a gel at the time when the sand grains were dropped into it. The pyrite, which forms part of the layers, must therefore represent the final crystalline product of a series of transformations starting, according to Doss's interpretation, with the gel of hydrated iron monosulphide (FeSH.OH). This assumption is based on the experiments of Feld, who demonstrated that the iron monosulphide, which results from the action of hydrogen sulphide on iron salts, is changed within a few days into amorphous iron disulphide, when hydrogen sulphide is allowed to pass through it in the presence of free sulphur and a reducing agent[1] (conditions realized in the natural sapropels).

In these experiments the precipitate of the monosulphide was of black color and voluminous. In changing into the disulphide it turned brown and settled into a compact mass on the bottom of the vessel, sharply separated from the liquid above and undisturbed by the bubbles of hydrogen sulphide passing through it; it also formed a "mirror" of metallic brown color on the vertical walls of the vessel.[2]

This sudden change in the physical properties of the precipitate of the monoxide, the sol of which is a typical suspensoid, certainly justifies the suspicion that the iron disulphide formed a gel, passing through an emulsoid state.

It should be emphasized that any one of the substances referred to above may be present in an oölitic grain as the binding colloid or as an accidentally enmeshed crystalloid. The latter case is illustrated by many of the numerous organic oölitic structures, like animal and vegetal pearls, gallstones, urinary calculi, and many other similar bodies occasionally found in the tissues of the animal body, in which the percentage of organic substance, in those cases the binding colloid, is often very small.

SIGNIFICANCE OF THIS INTERPRETATION

This brief survey justifies the assumption that most, if not all, oölitic and spherulitic grains were formed by at least one constituent substance changing from the emulsoid state to that of a

[1] W. Feld, *Zeitschr. für angew. Chemie*, XXIV (1911), 97–103.

[2] Feld, *op. cit.*, p. 101.

solid; that the spherical shape of the grains is due to the tendency of the droplets forming during this process of separation to coalesce; and that the difference between radial and concentric structure depends on the amount of other substance thrown out simultaneously with and mechanically enmeshed in the growing structure.

The chief value, at present, of this interpretation of the origin of oölites to the geologist lies in the fact that it gives a new direction to future work. The questions to be answered in each case are:

1. What factors determined the colloid dispersion of the salt and what was the medium of dispersion?

2. What caused the separation of the colloid from the dispersion medium?

3. What made possible the suspension of the growing spherite?

The chemical geologist will have to decide in each case whether the factors involved in the first two questions were physical (for instance, the presence of protective colloids) or chemical (for instance, the nature and quantity of other substances in solution) or biological (for instance, the action of bacteria).

INTERPRETATION APPLIED TO SEDIMENTARY OÖLITES

Shape of grains due to growth in suspension.—The last question, on the other hand, is of special interest to the stratigrapher. We were accustomed to think that calcareous or limonitic oölites owe their spherical shape to constant rolling on the sea (or lake) bottom. While it cannot be said that such an origin is impossible, there is experimental evidence which raises doubts in my mind as to whether agitation of the suspension or dispersion medium would ever allow of the formation of such structures. Besides, there are now very few cases left in which such an interpretation might seem necessary.

The alternating layers of silica and of carbonate of the pisolites form while the spherites are being carried up by the current of the flowing spring water. The layers of hailstones form as they fall. Limonitic oölites form in the gels of organic iron salts on the bottom of Swedish and Finnish lakes.[1] Oölites of bauxite and of limonite

[1] For references see F. Beyschlag, J. H. L. Vogt, and P. Krusch, *The Deposits of the Useful Minerals and Rocks*, translated by S. J. Truscott (London, 1916), II, 982.

form in residual clays.[1] The calcareous oölites of Great Salt Lake form suspended in the jelly-like masses of algae, as was described by Rothpletz.[2] Drew's artificial oölites formed in the agar-agar of his bacterial culture, and in Vaughan's experiments they grew in the soft amorphous calcareous muds which occur so abundantly on the shores of the Bahama Islands.

Apparent exceptions.—I know of only two cases which at first sight at least seem to form exceptions to the rule that oölites grow in free suspension.

1. Gaub, in a splendid paper, described oölites containing numerous microscopic shells of a Foraminifer classed with the Miliolidae (*Ophthalmidium ooliticum*).[3] These he considers to have been incrusting forms which attached themselves to small fragments of shells, crinoid stems, etc. (now forming the nucleus of the oölitic grains), and, being rolled about in the amorphous calcareous mud, held it mechanically and perhaps even localized its precipitation. The fact that a very similar, not incrusting, species of the same genus *Ophthalmidium* is very abundant in the same layers suggests the possibility that these minute shells were only mechanically inclosed in the growing oölite and that surface tension may be responsible for their tangential arrangement. Schade observed, for instance, that in some pearl-like gallstones the holesterin crystals were all arranged tangentially, enmeshed in the binding colloid.[4] Some of the shells within the oölitic grains are flattened on the side facing the center of the oölitic grain. Others, however, exhibit similar deficiencies on the outer side. Gaub interpreted the former as evidence of attachment, the latter as evidence of mechanical wear. They may, however, both be due to a small amount of solution during the growth of the oölite.

[1] C. K. Leith and W. J. Mead, *Metamorphic Geology* (New York, 1915), pp. 35–37; for literature on European "bean ores" see Beyschlag, Vogt, and Krusch, *op. cit.*, p. 990.

[2] A. Rothpletz, "On the Formation of Oölite," *Amer. Geologist*, X (1892), 279–82 (translated from *Botanisches Centralblatt*, LI [1892], 265–68).

[3] F. Gaub, "Die jurassischen Oolite der Schwaebischen Alb," *Geol. und palaeont. Abh.*, N.S., IX (1910), Heft 1. An earlier shorter paper, *N. Jahrb. für Min.*, etc., Part II, (1908), pp. 87–96, Pls. 7–8.

[4] Schade, *Kolloidchemische Beihefte*, I (1910) 385.

Since, at present, the original papers are inaccessible to me I cannot judge the degree of probability of this suggestion. It is, of course, possible that frequent interruptions in the normal process of growth of the oölitic grains, caused by a stirring of the calcareous muds during storms, permitted the *Ophthalmidia* to attach themselves to the grains and thereby to participate in their growth.

2. The second case comprises oölites in the formation of which filamentous algae are supposed to have had an active part. Such oölites were, for instance, recently described by Van Tuyl from the Ordovician of Iowa.[1] They contain in abundance "minute sinuous fibers similar to those which characterize the Girvanella type of calcareous algae." In oölites from the shores of the Red Sea, Rothpletz found "peculiar vermiform, and not rarely dichotomously branching, canals that are filled up with calcite."[2] In fresh-water springs and pools threadlike Schizophyceae are usually found associated in great numbers with the primitive types which cause the separation of the lime carbonate. Rothpletz, therefore, considered the vermiform structures of the oölites as "threadlike algae which were, of course, not themselves immediately concerned in the oölite formation, but by the company in which they lived were imprisoned with it." Since Van Tuyl states expressly that his oölites showed in addition to the supposed calcareous algae "good concentric and radial structure," there can be little doubt but that Rothpletz' interpretation may be applied to them directly. Similar canals might, however, also be produced by boring algae or fungi, the ramified canals of which are found permeating larger shells and pebbles as well as shells of Foraminifera in size comparable to the oölites.[3]

Relation of algae to oölites.—The rôle which Rothpletz assigned to such Schizophyceae as Glœocapsa and Glœothece in the formation

[1] F. M. Van Tuyl, *Science*, N.S., XLIII (1916), 171; *Jour. Geol.*, XXIV (1916), 792–97.

[2] Rothpletz, *Am. Geologist*, X, 280.

[3] J. E. Duerden, "Boring Algae as Agents in the Disintegration of Corals," *Bull. Amer. Mus. Nat. Hist.*, XVI (1902), 323–24. They were also described from Ordovician Foraminifera and from numerous Siluric fossils (see F. B. Loomis, "Siluric Fungi from Western New York," *Bull. N.Y. State Mus.*, VIII (1900), No. 39, 223–26, especially Fig. 3 on Pl. 16).

of oölites appears to have been generally misunderstood. The cells of these primitive algae correspond in size to the larger forms of bacteria.[1] Bodies resulting from the precipitation of lime on or in the thick, jelly-like membrane surrounding the minute cells would therefore have a diameter fifty to a hundred times smaller than that of the oölites. Such bodies were, in fact, observed by Rothpletz in the oölites from Great Salt Lake as well as in those from the Red Sea, and were found to be mechanically incased in the oölites like the filamentous algae. "In quite delicate sections the calcareous substance [of the oölites] . . . . is interrupted by scattered, minute granules. If we dissolve the section cautiously and slowly in very dilute acid, the granules remain behind exactly in their original position, and we recognize in them the dead and crumpled Glœocapsa cells" (p. 280).

From this it follows that if the Schizophyceae have at all an active part in the formation of oölites[2] it must be similar to that played by the closely related bacteria which separate calcium carbonate in the form of an emulsoid sol from solutions of calcium salts and thereby create conditions favorable for the growth of oölitic grains.[3]

The papers in which Wethered described Girvanella from many oölitic rocks of various ages[4] are, unfortunately, not accessible to me. The structure of certain calcareous oölites described by him, according to Rothpletz, seems "to have great resemblance to that of the Sinai oölite and is, perhaps, to be explained in the same manner." Others, however, judging from one of his figures reproduced in Harker's *Petrology for Students*,[5] represent true incrusta-

[1] Glœocapsa: 2 μ in diameter; Glœothece: 4–5 μ long; Anthrax bacillus: 6 μ long.

[2] Weighty reasons against this assumption were adduced by T. C. Brown, "Origin of Oölites and the Oölitic Structure in Rocks," *Bull. Geol. Soc. America*, XXV (1914), 754–57.

[3] As this process is probably due to a reaction of the calcium salts of the water with an alkaline excretion of the algae, we cannot, in this case, speak of "lime secreting" algae (cf. W. Pfeffer, *The Physiology of Plants*, I, translated by Ewart [Oxford, 1900], 133). Compare Drew's account of the action of denitrifying bacteria (*Carnegie Institution of Washington, Publication No. 182*, p. 30).

[4] E. Wethered, "On the Occurrence of the Genus Girvanella in Oölitic Rocks," etc., *Quar. Jour. Geol. Soc.*, XLVI (1890), 270–83; LI (1895), 196–206.

[5] Fourth ed., London, 1908, fig. 69, p. 261.

tions of organic fragments by the interlacing tubes of Girvanella and should therefore not be called oölites at all.[1] When exposed, true oölites may, of course, be incrusted in the same way.

SOURCES OF ERROR IN INTERPRETING ORIGIN OF OÖLITES

Secondarily deposited oölites.—Erroneous conceptions concerning the origin of oölites may arise if no clear distinction is made between layers in which the oölitic grains are found *in situ* and such in which they were redeposited after transportation. The secondary origin of oölitic deposits may be recognized by the practical absence of a matrix, by the uniformity of size of grains (indicating sorting), by cross-bedding, or by the presence of substances accidentally enmeshed in the oölitic grains which are foreign to the surrounding matrix, etc. In such cases the oölitic grains were either washed by waves or currents from their place of origin and redeposited in water, or they were carried inland by the wind where they may have formed dunes, as they do now on the shores of the Red Sea and of Great Salt Lake.[2] The recognition of such secondary oölites and their correlation with synchronous primary deposits may, under some circumstances, convey valuable information to the paleogeographer.

It is often quite difficult to prove satisfactorily the origin *in situ* of an oölite. For this we must, in many cases, rely entirely on a microscopic study of the relation existing between the matrix and the oölitic grains. In some cases, however, the characteristic incrustations and massive growths, called "stromatoliths" by Kalkowsky,[3] are found associated with the oölitic grains and by their presence prove the primary nature of the oölites, as, for instance, in the Upper Triassic (Rhaetic) of England, the Mississippian of Belgium, the Lower Bunter of Northwestern Germany, the Tertiary of the Rhine Valley, etc.[4]

[1] The term "pseudoölite" has been used for grains imitating oölites; for instance, minute pellets of dense limestone in a limestone matrix (cf. O. M. Reis, *Geognostische Jahreshefte*, XXII [1909], 228).

[2] J. Walther, *Lithogenesis der Gegenwart* (Jena, 1894), pp. 659, 699, 849; A. W. Grabau, *Principles of Stratigraphy* (New York, 1913), pp. 468, 472.

[3] Kalkowsky, *Monatsber. Deutsch. geol. Ges.*, LX, I (1908), 68–125.

[4] Cf. O. Reis, "Ueber Stromatolith und Oolith," *N. Jahrb. für Min.*, etc. (1908) Part II, pp. 114–38.

Under the microscope these stromatoliths exhibit a structure of delicate layers identical with that of the oölites, with which they are often connected by all stages of transition.[1] They differ greatly, both in structure and in origin, from the coarse calcareous crusts which are formed by thick, felted masses of fresh-water algae and mosses on shells and pebbles.[2] The two can easily be distinguished when found associated in the same formation, as, for instance, in the Miocene limestones of the Rhine valley.[3]

The stromatoliths are the sedimentary equivalent of the calcareous and siliceous "sinter" of the hot springs; stromatolithic crusts of limonite are commonly found in lake and bog ores.

In the simple experiments with iron chloride, described in the first part of this paper, similar growths were observed in the same cases in which spherites with oölitic structure were produced. In these experiments flat expansions formed below the massive crust which sealed the liquid, and, to a smaller degree, also at the bottom of the vessel, corresponding in thickness to the radius of the oölitic grains and showing the same delicate concentric structure. There can be little doubt but that they represent the experimental reproduction of stromatoliths.

Subsequent alteration of oölites.—Another, more fundamental, source of error in the interpretation of the origin of oölites has been the more or less altered condition of most fossil oölites. Many calcareous oölites, for instance, have suffered complete recrystallization which, starting usually in the center of the grains,[4] replaces their original structure by a few crystals, or even a single large calcite individual, concentrating all impurities in a thin layer at their periphery. Such extreme cases have been inter-

[1] Cf., e.g., Bucher, *Geogn. Jahresh.*, XXVI (1913), 78–79, and Pl. I, Fig. 22.

[2] Cf., e.g., J. M. Clarke, "The Water Biscuit of Squaw Island, Canandaigua Lake, N.Y.," *Bull. N.Y. State Mus.*, VIII (1900), No. 39, 195; W. Schmidle, "Postglaciale Ablagerungen im nordwestl. Bodenseegebiet," *N. Jahrb. für Min.*, etc. (1910), Part II, 105–22.

[3] Bucher, *op. cit.*, pp. 80–81.

[4] Cf. the illustrations and the discussion of the mechanism of this process in Reis, *Geogn. Jahresh.*, XXII (1909), 227–31, and Pl. 11, Figs. 25–30.

preted as incrusted gas bubbles secondarily filled with calcite ("ent-oölites").[1]

In other cases the substance of the oölitic grains has been completely changed, in some even before final deposition, in others during the diagenesis of the sediment, or still later through metasomatic or katamorphic processes, as in the dolomitic oölites,[2] some siliceous oölites,[3] and the great variety of oölitic iron ores, the interpretation of which, in most instances, is still far from being satisfactory.

[1] C. W. v. Gümbel, *N. Jahrb. für Min.*, etc., 1873, p. 302. The incrustation of air bubbles by calcium carbonate was observed by Knop in the hot springs at Nauheim. Cf. *ibid.*, 1874, p. 285.

[2] Cf., for instance, W. H. Sherzer and A. W. Grabau, "The Monroe Formation of Southern Michigan and Adjoining Regions," *Mich. Geol. and Biol. Surv.*, Publ. 2, 1910, pp. 35–37; T. C. Brown, "Origin of Oölites and the Oölitic Texture in Rocks," *Bull. Geol. Soc. America*, XXV (1914), 759. For European occurrences see the textbooks of Zirkel (*Petrography*), Tschermak, etc.

[3] Cf., for instance, the siliceous oölites of Pennsylvania, in Brown, *op. cit.*, pp. 760–68.

RHYTHMIC BANDING OF MANGANESE DIOXIDE IN RHYOLITE TUFF

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University of Missouri

The material upon which this study is based was collected by the writer on the south slope of Tumamoc Hill, the largest of a group of low hills of the same name about a mile west of Tucson, Arizona. The Desert Laboratory of the Carnegie Institution of Washington is located on the north slope of this hill. The geology of this region is presented in a paper[1] by C. F. Tolman, Jr.

As the writer had been unable to find any description of a similar occurrence of an eccentrically banded structure of manganese dioxide in rocks, it seemed to him that a description of this occurrence would be of interest. The structure will be referred to as rhythmic banding. This term seems to be the best, as the structure cannot be called an orbicular structure, which it resembles to a certain extent, because that term is applied to certain crystalline aggregates in igneous rocks.

Mode of occurrence.—The specimens of manganese dioxide were found in the talus at the foot of a bed of rhyolite tuff which outcrops on the southern slope of Tumamoc Hill. The tuff, according to Professor F. N. Guild,[2] consists of volcanic ash with numerous inclusions of pumice and darker, more basic, fragments. The volcanic ash consists of glass, fragments of quartz, feldspar, ferromagnesian minerals, and kaolinized material. Professor Guild gives the following analysis:

SiO_2	73.59
Fe_2O_3, Al_2O_3	13.95
CaO	1.41
MgO	0.75
K_2O, Na_2O	11.23

This analysis shows that the rock is very siliceous.

[1] *Publication No. 113, Carnegie Institution of Washington*, pp. 67–82.

[2] F. N. Guild, *Publication No. 113, Carnegie Institution of Washington*, p. 81, and *American Journal of Science*, XX (1905), 314.

An analysis of the material to determine the percentage of MnO_2 was made by Mrs. W. A. Tarr. It was found that it was merely a stain which was readily removed from the tuff by acids. The amount of MnO_2 present was 0.82 per cent.

At the point where the material was collected the rhyolite tuff is about 100 feet thick. It is overlain by a basalt and rests upon an andesitic conglomerate. As none of the specimens could be located on the face of the bluff it is not known whether the structure formed after the material had accumulated in the talus or while it was still in place. Likewise it cannot be determined from which part of the bed of tuff the material was derived.

Description of the rhythmically banded structure.—The light- to dark-brown color of the rhythmically banded manganese dioxide in the light-gray tuff gives the rock a very striking appearance (Fig. 1). The amount of manganese dioxide in each structure is small (see analysis above), for the tuff is merely colored and is not replaced in any way. This staining process was greatly aided by the very porous character of the material. Practically all the banded areas are circular or elliptical, the former shape predominating, though a few are irregular in outline. In size they vary from 30 mm., as a maximum, down to mere brown specks.

All the structures show either eccentric or concentric banding, this being true of those which are as small as 1 mm. in diameter. The banding is very delicate in most of them and is due to variations in the shade of the brown color. The bands are usually about a fraction of a millimeter in width, but in some of the large structures the bands are as much as 2 mm. in width, and occasionally the central zone has a diameter of 9 mm. and is uniformly tinted throughout (see Fig. 1). There are sometimes ten to fifteen bands in these larger structures. The rings are not absolutely uniform in their spacing or in their intensity, but they are so nearly so that slight variations in the composition of the solutions would account for the differences. The photographs do not show the bands clearly because of the small differences in light values between the zones. (See the drawing, Fig. 2.) The manganese dioxide affects the color of the finer pumiceous material, but as a rule does not change the color of the fragments of quartz, biotite, and other minerals

within the area of the banding. The outer part of the structures is usually darker than the interior.

The remarkable thing about these structures is that in a majority of them the bands are not concentric. In one case the nucleus was

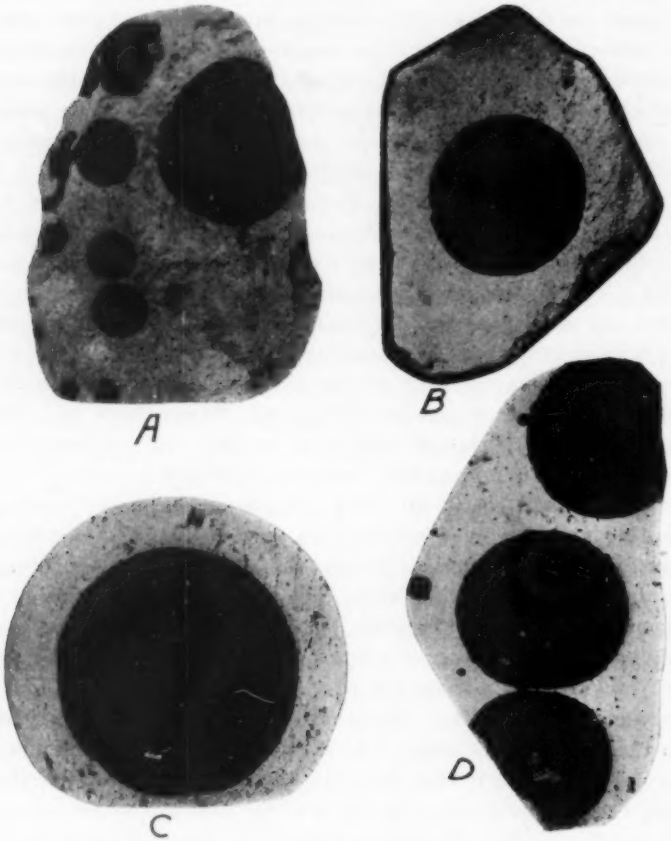

FIG. 1

A, Several spheroids in one piece of tuff
B, Spheroid showing the rings
C, Spheroid somewhat enlarged, showing rings
D, Three eccentric spheroids, slightly enlarged

8 mm. from one side and 20 mm. from the other, yet the structure was spherical. The majority have their nuclei to one side of the true center. It was this peculiar zoning that first attracted the writer's attention.

The only regularity of arrangement of the banded structures in the tuff is their relationship to the surface, as they are more numerous near the exposed surface of the fragments of tuff. All of the specimens on hand show weathered faces on one or more sides, thus indicating that the structures are definitely related to the surface of the talus blocks from which they were obtained. The largest structures are usually an inch or so from the surface, the intervening spaces being filled with numerous smaller banded areas, which not infrequently coalesce. A larger one may partially or wholly envelop a smaller one, apparently without affecting its color in any way. Again, two large ones may be so close that only a line separates them, yet each is distinct, or they may interfere and produce a lobate structure.

FIG. 2.—Tracing of an eccentric structure. Actual size.

A rather striking feature is the position of the nuclei in those forms that are eccentric and that lie near the weathered surface of the talus block. The nuclei are on the side of the structure which is nearest to the weathered surface, and the bands widen upon the opposite side. This may be definitely connected with the origin of the rhythmic banding. The largest structures and also those most nearly circular lie farthest below the surface. These, as a rule, are also the most perfectly banded structures.

Suggestions as to the origin of the rhythmic banding in the manganese dioxide.—The origin of the rhythmic banding is an interesting problem, and the two following suggestions appear to be the most feasible explanations of the phenomena: (1) the manganese was leached out of the tuff and deposited near the surface of the blocks, or (2) some mineral in the tuff furnished the manganese, the dioxide forming in the zone around it.

1. That the aggregation of the manganese into rhythmic zones might be due to the same process that produces the well-known

dark coating called "desert varnish," which is found on surface materials throughout the desert region appears to be plausible. This coating is thought to be due to the evaporation of water drawn from the interior by capillarity, the salts in solution being deposited at the surface. The writer has never been able to find an exact statement of the chemistry of this process, and he feels inclined to doubt the applicability of the method suggested, because iron and manganese salts are very difficult of solution even under favorable conditions, and it is well known that the arid climate of Arizona and New Mexico favors oxidation and tends to inhibit reduction, which is a necessary step in the solution of the salts of these elements.

However, in the case of the tuff the solution could circulate through it readily, as it is very porous, and if proper solvents were present some manganese might be dissolved. Upon evaporation at or near the surface, where oxidizing conditions prevail, the manganese would be thrown down as the oxide. Once started, the structure would grow by fresh additions from the outside. As the solutions were moving outward it is to be expected that the growth on the inside would be most rapid, and thus the eccentric rings would develop. Variations in the amount of manganese and the hydration of the resulting oxide would account for the color variations. At a distance from the surface the structure would be nearly circular, because of the more uniform addition of material.

It should be noted, however, that rhyolites are usually very low in manganese, which is against the theory that the manganese has been derived from the rhyolite tuff. Such rocks nevertheless occasionally contain minerals which are high in manganese, the garnet spessartite being especially common in them. Such a mineral, even though present in small amounts, when broken and scattered through a block of tuff might furnish a fair source of manganese. Likewise biotite sometimes contains manganese, and considerable biotite (nearly always hydro-biotite) occurs in the tuff. These are therefore possible sources of the manganese.

2. The manganese dioxide of the rhythmically banded structures may have originated from and developed around a fragment

of some manganese mineral. No definite evidence of the presence of such a mineral could be found, although one would be supposed to be occupying, or to have occupied, the center of the structures. The original mineral may have been spessartite, which, as has been noted, occurs in rhyolites, as at Rosita Hills, Colorado. It might also have been some manganese-rich ferromagnesian mineral, such as biotite, or one of the pyroxenes or amphiboles.

Water could readily enter the porous tuff and attack the spessartite. The manganese would be taken into solution largely by the water from the immediate rainfall and probably in the form of the carbonate. It could be carried out some distance (about one inch in the larger structures) before deposition ceased. Deposition would be caused by the oxidation of the manganese salt to manganese dioxide, a process that would be favored by the arid climate of the region.

A study of the bands favors the view that they are due to the same process as is the formation of Liesegang's rings, also known as rhythmic banding.[1] Once the manganese is in solution it will diffuse outward through the tuff. Holmes's demonstration that the rings may be produced in loosely packed flowers of sulphur shows that gels are not essential for their development. The porous tuff would be analogous to the flowers of sulphur in permitting the diffusion in this case.

The manganese solution would diffuse outward at a rate dependent upon its concentration. As it mingled with other solutions containing oxygen, the concentration of the respective ions would increase until a labile condition occurred, when precipitation would take place, thus producing a ring. The color of this ring would depend upon the concentration of the solution and in part upon the hydration of the resulting oxide. The manganese solution would then move on (provided its rate of diffusion exceeded that of the other solution) through the zone depleted of oxygen until a second

[1] Recent discussions of rhythmic banding or precipitation are given in the following papers: J. Stansfield, "Retarded Diffusion and Rhythmic Precipitation," *Am. Jour. Sci.*, 4th series, XLIII (1917), 1–26; H. N. Holmes, "Rhythmic Banding," *Science*, New Series, XLVI (1917), 442; J. Stansfield, "Rhythmic Precipitation," *ibid.*, New Series, XLVII (1918), 70.

concentration occurred. As the solutions became weaker the rings would become farther and farther apart unless the concentration of the oxidizing solution became stronger. The width of the zones between the rings would depend upon the relative rates of diffusion of each solution. That there was a slight change in the concentration of the solution as long as there was a source of the manganese is shown by the gradually increasing intensity in color in the outer portions of the structures. The larger fragments of minerals in the tuff are uncolored because of their density.

The eccentric character of the banding is probably the result of several factors. The rate of diffusion of the two solutions was probably different in different directions. The rate of diffusion inward from the surface of the oxidizing solution was probably most rapid, hence the oxidizing solutions met the manganese solutions nearer the nucleus on the side nearest the surface. This interpretation is in accord with the fact that the majority of the structures show wider zones of rings on the side opposite to the surface, where the rate of diffusion of the manganese solutions is greater than that of the oxidizing solutions. Another factor may have been the varying porosity of the tuff, although this is not so likely as the foregoing, because it is not probable that the majority of the banded structures should have the same variation in porosity on the same side. When the blocks of tuff were lying in the proper position downward diffusion as influenced by gravity might aid in producing the eccentric rings. Unlike in laboratory experiments, where the rhythmic banding is produced in a gelatine of uniform composition and density, the rhythmic banding in nature would find varying factors on all sides, hence one should really expect the banded structures to vary from perfect rings. The varying width of the rings themselves is due to the variable character of the solutions. It would seem that this suggestion as to the origin is the better of the two and, if correct, furnishes an interesting example of rhythmic banding in rocks.

Summary.—Rhythmically banded structures of manganese dioxide are found in rhyolite tuff near Tucson, Arizona. These structures are eccentric, which is an unusual mode of occurrence.

They are apparently due either to the manganese being derived from the surrounding tuff and aggregated into the banded forms, precipitation being due to oxidation, or to the mangagese dioxide being derived from a mineral located at the nucleus of the structure and being precipitated in successive rings by rhythmic precipitation following the mingling of the outwardly moving manganese solution with one of oxidizing character. The latter view is believed to be the most probable.

THE RELATION OF THE FORT SCOTT FORMATION TO THE BOONE CHERT IN SOUTHEASTERN KANSAS AND NORTHEASTERN OKLAHOMA[1]

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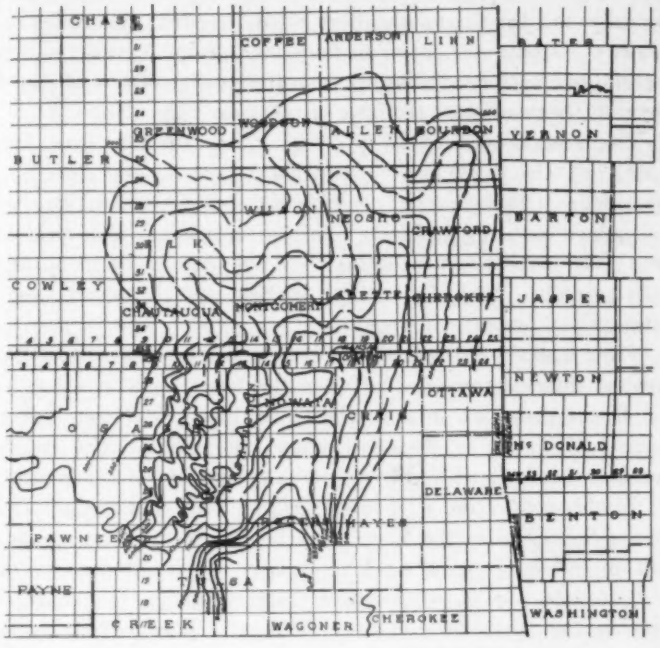
The Fort Scott formation is a limestone with interbedded shales of the lower Pennsylvanian system in southeastern Kansas and northeastern Oklahoma. The outcrop of this formation extends from the region north and east of Fort Scott (T. 25 S., R. 25 E.), Kansas, southwestward to several miles south and east of Broken Arrow (T. 18 N., R. 14 E.), Oklahoma, where it is thin and too much covered for further mapping. The Boone chert (Osage series) of the Mississippian system is a hard, cherty limestone which outcrops in the extreme southeastern part of Kansas and the northeastern corner of Oklahoma. These two limestone horizons dip gently to the west and are separated in this area by the Cherokee formation. The Cherokee formation (Pennsylvanian) consists largely of shale with a few limestone and sandstone beds. Toward the southern edge of the area under discussion other formations appear between the Boone chert and the Fort Scott formation. They are known as the Mayes[2] limestone, the Fayetteville, the Pitkin, and the Morrow formations and consist largely of limestone with some shale. These affect only the area south of the territory discussed.

The map on page 619 shows a number of isobathic lines, or lines connecting points of equal intervals, between the top of the Fort Scott formation and the top of the Boone chert. These intervals were determined from measured geologic sections on the outcrop of the formations and from about five hundred records of wells which have been drilled to the Boone chert, west of the outcrop

[1] Published by permission of the chief geologist, Empire Gas and Fuel Company.

[2] L. C. Snider, *Okla. Geol. Surv. Bulletin No. 24*, p. 27.



CONTOUR MAP
SHOWING INTERVAL BETWEEN FT. SCOTT LIMESTONE AND THE BOONE CHERT OF SOUTHEASTERN KANSAS AND NORTHEASTERN OKLAHOMA.

of the Fort Scott limestone. The records have been studied carefully and the top of the Fort Scott limestone determined by means of "spiderweb" cross-sections made from several thousand well records scattered uniformly from the locality of the outcrop on the east, westward past the edge of the area.

The interval between the Boone chert and the Fort Scott limestone, i.e., the thickness of the Cherokee shale and Fort Scott limestones, at their outcrop near Pryor Creek, Oklahoma, has been determined as being 500 feet. This is considerably less than has been given heretofore for this interval, but the measurements have been carefully checked by three parties and the results are in substantial agreement.

From a study of the isobathic lines it will be observed that the greatest intervals recorded between the Fort Scott limestone and the Boone chert are in a northeast-southwest line from Labette County, Kansas, to Rogers County, Oklahoma. The interval becomes smaller both to the east and to the west of this line.

In this connection it is interesting to note that the thickness of the limestone in the Fort Scott formation averages 20 to 40 feet on the outcrop and thickens rapidly westward to an average of 80 to 100 feet in northeastern Osage County, Oklahoma, and southeastern Chautauqua County, Kansas. Thence the formation thins to the west until it can scarcely be recognized in the well logs in west central Osage County, Oklahoma, and western Chautauqua, Elk, and Greenwood counties, Kansas. The alignment of greatest limestone thickness in the Fort Scott formation parallels the northeast-southwest alignment of greatest interval between the Boone chert and the Fort Scott formation.

The greater thickness of the Cherokee shale along the line from Labette County, Kansas, to Rogers County, Oklahoma, as shown by the isobathic lines, is interpreted as indicating the deeper part of the depositional basin in which the Cherokee was deposited. The lowest beds in this portion of the basin do not appear to have been deposited in the areas to the east and west, which were probably either land or covered intermittently by shallow water. It is only in this deeper part of the basin that we have the thick, lenticular sands, such as the Bartlesville, Burgess, and Tucker, which are

so productive of oil and gas, in northeastern Oklahoma and southeastern Kansas. These sands are present in the lower one-third of the Cherokee formation and are practically confined to the area inclosed within the 400-foot isobathic line.[1] The sands higher in the section extend farther to the west. The lenticular nature of the sands in the lower part of the formation indicates an oscillating sea, and the occurrence of the greatest limestone thickness of the Fort Scott formation, to the west of the deepest part of the Cherokee basin, indicates a shifting of the basin in that direction as the Cherokee time interval progressed.

Irregularities appear in the isobathic lines, as in northern Chautauqua County, Kansas, for example. These irregularities appear to be due to the presence of troughs during the early history of the basin. These troughs may have been caused by erosion of the Boone chert before the deposition of the Cherokee shales or may have been formed by downwarping during the deposition. The trough mentioned is shown as a flat on the Boone chert contour map of the Kansas Geological Survey.[2]

Many smaller irregularities appear on the southwestern side of the basin, indicating that the surface of the Boone chert was considerably eroded by the time the Pennsylvanian sea encroached upon the land to the west. This is well shown by the isobathic lines in Washington and Osage counties, Oklahoma. In several places the presence of old river valleys may be indicated by the successive curving in of the isobathic lines, such as the one extending from the north edge of T. 23 N., R. 12 E. to T. 25 N., R. 10 E., Osage County, Oklahoma.

The writer is indebted to Mr. A. W. McCoy, under whose direction the work has been carried on, and also to Dr. L. C. Snider, for valuable suggestions.

[1] The productive sands in the fields farther west, which have generally been correlated with the Bartlesville sand, are considered from our studies to be at other horizons.

[2] *State Geol. Surv. of Kansas, Bulletin No. 3*, p. 197.

A FORM OF MULTIPLE ROCK DIAGRAMS

FRANK F. GROUT
University of Minnesota

A number of suggestions have been made for rock diagrams, designed to show the variation in several constituents through a series of rocks, and a modification is here offered of a method proposed by Adams.[1] He used the chemical analysis directly. This gave a conspicuous line for silica in nearly every analysis. It occurred to the writer that the relative proportions of constituents could be seen more clearly if the analyses were recalculated to the norms,[2] in which a larger number of constituents are usually present in notable amounts. Since the mode sometimes differs from the norm, this method is of course subject to any criticism of the norm as a method of stating rock composition; but it has some advantage over the simple plotting of chemical constituents. Furthermore, the method applies to the mode almost as well as to the norm. Those who do not like the norm can measure or calculate the mode, but in this case relatively few constituents ordinarily attain prominence. It will be recalled that a single feldspar in the mode may be three in the norm, and that certain ferromagnesian minerals in the mode may be divided in the norm.

As a further modification of Adams' method the writer finds it desirable not to plaster the individual rock diagrams together, but to clamp them into position leaving them free for rearrangement, as they are studied from various points of view. Thus in a gabbro (see "A Type of Igneous Differentiation," p. 627) it was of interest to arrange the rocks in what might be called stratigraphic position to see if the magnetite showed a tendency to concentrate at any special horizon; while in the study of differentiation it was

[1] F. D. Adams, "A Graphical Method of Representing the Chemical Relations of a Petrographic Province," *Jour. Geol.*, XXII, 689.

[2] Whitman Cross, J. P. Iddings, L. V. Pirsson, and H. S. Washington, *Quantitative Classification of Igneous Rocks*. University of Chicago Press, 1903.

of interest to try first an arrangement in the order of increasing albite, and then in the order of increasing anorthite, and so on. The sequence and the exceptional rocks are noted in the process of arrangement even more readily than in the photographs.

Attention may be called to certain significant points shown by the diagrams (Figs. 1, 2, and 3). Norms were selected at random

FIG. 1.—A multiple diagram of a series of rocks from the Alaskose subrang in the quantitative classification. The predominance of quartz and alkali feldspars is clear.

in the subrangs in the quantitative system. The contrast in the three pictures is evident; so also is the relative uniformity in the norms of a single picture. A further remark is to be made in this regard, however. The uniformity is clear in the first two but not so clear in the third. This group of rocks is from the class of salfemanes; that is, salic and femic minerals are present in about equal amounts. Salfemanes are grouped according to the relations

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of salic minerals, as far as the classification is commonly used. In the subrang Auvergnose the diagram shows that the prominent femic mineral may be either diopside, hypersthene, or olivine. For this reason the diagrams of salfemane subrangs may show a great deal of variation in the femic minerals. However, if the

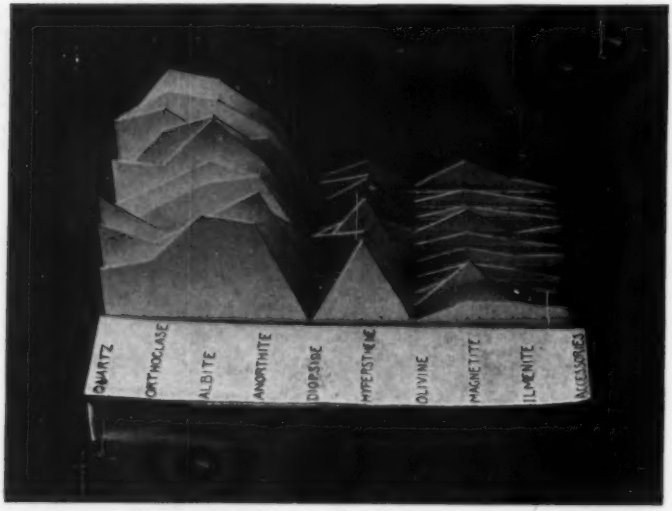

FIG. 2.—A multiple diagram of a series of rocks from the Harzose subrang in the quantitative classification. The quartz and feldspars are predominant here also, but the more siliceous minerals here give way to increased amounts of anorthite.

classification is carried one step farther, to the "grad," these varying rocks would fall in different grads. As a whole it is clear that analyses of a single group in the quantitative classification show their relationship conspicuously in the diagram.

Attention may also be called to the contrasting series shown in the diagrams of "A Type of Igneous Differentiation." The variation in the gabbro series at Duluth shows no tendency to develop a type intermediate between the gabbro and the red rock. The second picture, the red rock, seems to be a strikingly different class of rocks.

In summary the method shows the composition of a series of rocks, with the following advantages. There are no excessive peaks except in case of some rare monomineralic rocks. The diagram can be based on either norm or mode. The cards can be rearranged for the study of each mineral, or the geographic or "stratigraphic"

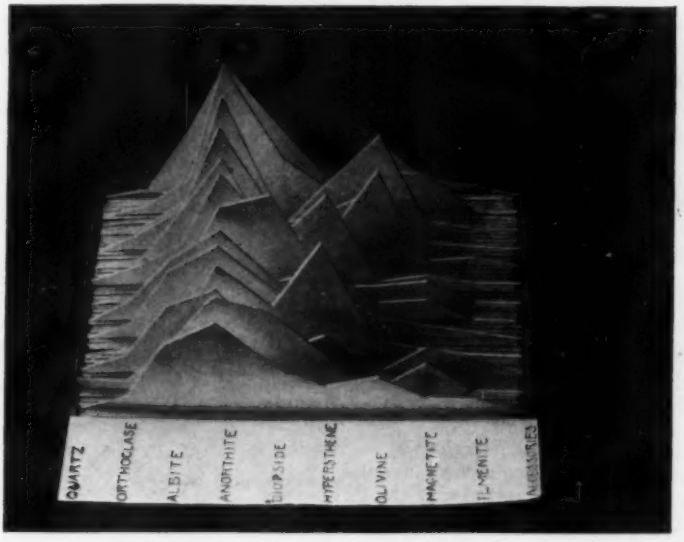

FIG. 3.—A multiple diagram of a series of rocks from the Auvergnose subrang of the quantitative classification. Quartz is negligible and anorthite is prominent. The femic constituents are prominent in this figure but are not uniform. One rock shows abundant diopside, one hypersthene, one olivine.

position of the rocks. Certain features of the norm classification are easily visualized by the diagram.

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A TYPE OF IGNEOUS DIFFERENTIATION[1]

FRANK F. GROUT
University of Minnesota

CONTENTS

INTRODUCTION
THE ROCKS OF DULUTH
THE GABBRO
- Peridotite phase
- Troctolite phase
- Anorthosite phase
- Magnetite phase

THE RED ROCK
- Introduction
- Description
- Gradation and relations
- Origin of the red rock

RELATION OF ROCK TYPES TO POSITION
DIFFERENTIATION
- Introduction
- Processes of differentiation
- Crystal settling versus convection
- Double differentiation

COMPARISON WITH OTHER DISTRICTS
- Scarcity of intermediate rocks
- An argument for immiscible separation

SUMMARY

INTRODUCTION

This paper begins with a summary description of the rock types of the Duluth gabbro formation, and suggests the processes by which they formed. Since there are similar rock series in other districts, where the relations of large intrusions are not so clear, or where the study has been less detailed, it is suggested that the same processes are indicated in those districts. This type of differentiation, therefore, is not at all unique.

[1] Published by permission of the Directors of the Minnesota Geological and Natural History Survey and the United States Geological Survey. Part of a dissertation presented at Yale University.

THE ROCKS OF DULUTH

The Duluth gabbro and its differentiates are intrusive into Middle Keweenawan flows, probably at a considerable depth. At Duluth it is evident that a feldspathic gabbro was intruded and cooled before the main mass of more basic gabbro was intruded. The mass is so large that it must have required thousands of years to cool, plenty of time for its differentiation into the many types now found. Some differentiates assume an intrusive relation to those earlier to crystallize, the most conspicuous case being the intrusion of "red rock," or granophyr, into gabbro. When studied in detail the mass shows by the intimacy of the geologic connection that, with all its variety, it is essentially a single geologic unit. Not only is the red rock related to the gabbro by association and intermediate phases, but over most of the area the two portions of the gabbro cannot be distinguished. Even at Duluth the two masses are not everywhere distinguishable. The averages differ only about 10 per cent in the amount of feldspar. It is believed that no great error will be introduced if the whole mass of data on the Duluth gabbro is considered as a unit. The main gabbro at Duluth and in many other outcrops is conspicuously banded.[1] The form has been named a lopolith[2] (Fig. 1).

The descriptive petrography of the formation need not be rewritten here in detail.[3] However, this study adds a few points from the type locality, where the exposures are exceptionally clear. The new data also make it possible to present a consistent, though not at all final, summary of the petrography of the whole mass.

THE GABBRO

The diagrams of the modes from measurements (Fig. 2) and the norms from analyses (Figs. 3 and 4) show the variation in the two gabbro masses at Duluth, without regard to position in the mass. It is evident that no simple linear series could be arranged on the

[1] Frank F. Grout, "Internal Structures of Igneous Rocks," *Jour. Geol.*, XXVI (1918), 439.

[2] Frank F. Grout, "The Lopolith," *Am. Jour. Science*, XLVI (1918), 516.

[3] The references and a correlation of the varying nomenclature are given by A. N. Winchell in *U.S. Geol. Sur. Mon. 52*, pp. 395–407.

basis of mineral composition. The main gabbro types shown in the diagram, even those of extreme composition, occur as alternating bands.

The average gabbro is gray when fresh and weathers nearly white. The texture is medium to coarse, granitoid to ophitic (see Fig. 5). The order of crystallization is in most cases plagioclase, olivine, magnetite, and augite. Olivine is not conspicuous in the

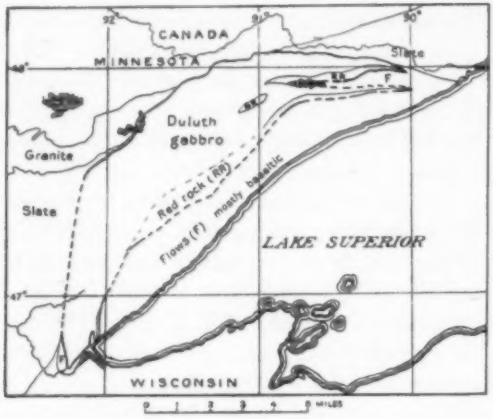

FIG. 1.—Sketch map of the Duluth gabbro area

average gabbro except on the weathered surface, where, being highly ferruginous, it turns to a bright brown, contrasting with the darker augite and iron ores. There is very little alteration. The character of the main minerals is surprisingly constant from end to end of the series of outcrops. All the olivine has about 30 per cent FeO whether in peridotite or anorthosite. There are few outcrops in which the feldspar differs much from Ab_1An_2. The pyroxene, with few exceptions, is augite low in lime.

The rocks of the gabbro series may be classified as normal gabbro, olivine gabbro (and the corresponding diabase, Fig. 5), troctolite, peridotite, magnetite gabbro, and anorthosite. Several specimens might show some further variation, but their occurrence is local and there is no evident importance in the distinction. The

pegmatitic phases have been discussed elsewhere.[1] The analyses tabulated below show the composition of the abundant types.

Peridotite phase.—Bands of peridotite occur in the banded gabbro a few yards above the base. The large bands are over

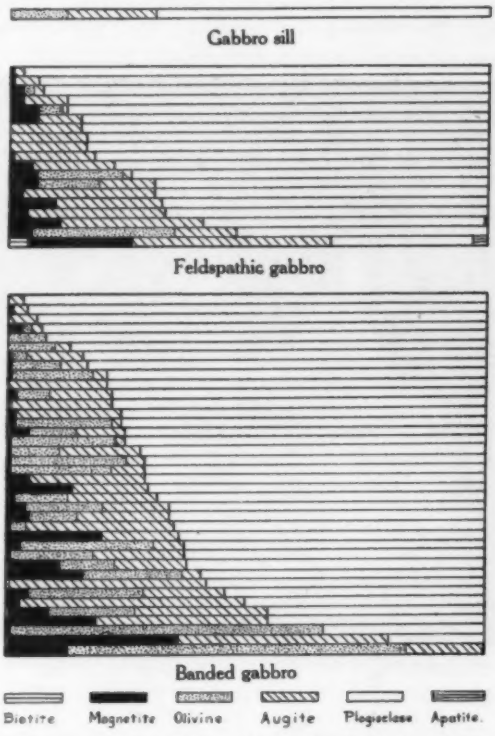

FIG. 2.—Diagram of measured modes of Duluth gabbro

15 feet thick and somewhat variable. They are nearly black, weathering rapidly to a crumbling brown soil. Analysis number 2 in Table I shows the chemical composition, and the diagram (Fig. 2) indicates the mineral composition.

[1] Frank F. Grout, "The Pegmatites of the Duluth Gabbro," *Econ. Geol.*, XIII (1918), 185.

Troctolite phase.—Troctolite, rich in olivine, like that described by Winchell,[1] occurs from the center to the base of the mass, in scattered bands. See analysis number 6 in the table. The proportion of olivine to plagioclase in the several troctolites varies widely, so that the rocks approach peridotite on one side and anorthosite on the other.

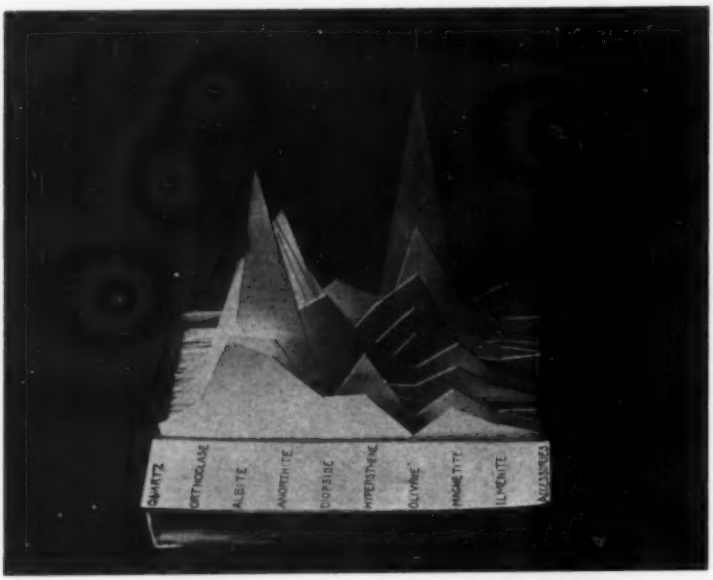

Fig. 3.—Diagram of the norms of analyses of gabbro at Duluth. Many phases have not yet been analyzed.

Anorthosite phase.—At Duluth the early feldspathic gabbro probably contains over 80 per cent plagioclase. Large parts of it by a slight process of differentiation become anorthosite. Analysis 3 of the table is a fair sample, but large masses are even purer feldspar. The later more basic gabbro has less anorthosite, but thin bands of it are not at all rare. An outcrop in Sec. 26, T. 50 N., R. 15 W., resembles the famous anorthosite inclusions in diabase

[1] A. N. Winchell, "Gabbroid Rocks of Minnesota," *Am. Geol.*, XXVI, 281–85.

sills along the shore of Lake Superior. The rock is a conspicuously spotted one (Fig. 6). The darker spots are large poikilitic olivine grains inclosing plagioclase and the white ground mass is feldspar with only a small trace of magnetite. Unfortunately the boundaries of this spotted rock are concealed.

Magnetite phase.—It is possible to find specimens and thin bands of gabbro near Duluth bearing as much as 36 per cent of titaniferous

FIG. 4.—Diagram of the norms of analyses of red rock of the Duluth gabbro formation.

magnetite. The bands are near the center of the gabbro, which is nearly three miles thick. There is no olivine in the magnetite rock, but augite is more abundant than in the average gabbro. The band shows fluxion structure, but the minerals seem to have crystallized about simultaneously, magnetite late in some (Fig. 5). Similar bands in Cook County, one hundred miles northeast, much larger and richer in magnetite, make up the titaniferous iron ores for which the gabbro is famous.

THE RED ROCK

Introduction.—The "red rock" has purposely been left out of the discussion of variations from the gabbro, not because it differs from the gabbro more radically than anorthosite differs from peridotite, but because its geologic relations are very different. It has not been seen as bands in banded gabbro. The change from gabbro to red rock is somewhat abrupt and without alternation. The gray gabbro rapidly gives place to a bright rèd rock very different from the gabbro in mineral, chemical, and physical characters.

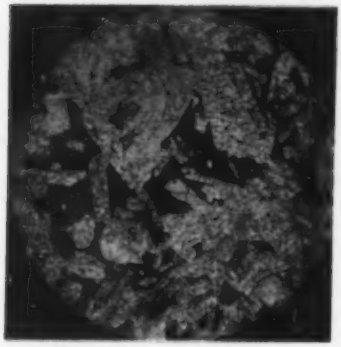

FIG. 5.—Thin section of Duluth gabbro showing diabasic texture. White to light gray, basic labradorite; dark gray, augite; black, magnetite which is late to crystallize. Plain light, ×20.

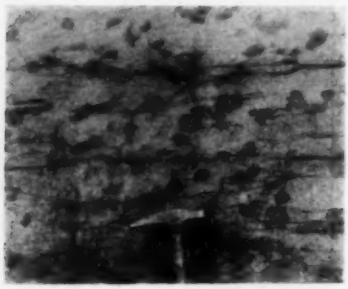

FIG. 6.—Spotted anorthosite. The dark areas are olivine crystals, which poikilitically inclose thousands of smaller plagioclase grains.

The "red rock" has become widely known under this name because of its brilliant color and the difficulty of giving it a more accurate classification. Some confusion may arise also from the fact that red felsitic flows appear in the Keweenawan series. The rock here discussed is intrusive and granitoid.

The chief outcrops near Duluth are irregular patches at the top of the main gabbro and apophyses into its roof; it occurs also near the top of the earlier feldspathic gabbro, in a large sill close above the gabbro, and in some small dikes near the bottom of the gabbro.

Description.—The texture varies from sugary near contacts to very coarse in certain patches. The rock is peculiarly friable, so that

hand specimens can hardly be trimmed from it. A striking local variation contains long needles of dark minerals in a red matrix. In thin sections it is micropegmatitic, varying to granitoid in some large masses. Miarolitic cavities are numerous in some places. Variability is as characteristic of the minerals as of the textures. The chief red mineral is a feldspar stained with considerable hematite and badly kaolinized. Probably most red rock contains two feldspars; zoning is especially common in the phases grading into the gabbro. Quartz, though abundant, is rarely visible except with the microscope as an intergrowth. Hornblende is the chief ferromagnesian mineral, but it is fibrous and mixed with secondary minerals as if itself secondary. Biotite is rare and in most cases secondary.

A sample of the red rock was selected from the type locality for analysis (number 25 of the table), and while it cannot fully represent so variable a rock, it shows some features in common with earlier analysis also quoted in the table. Nearly all the norms include corundum; many also include hematite. For a rock consisting largely of graphic intergrowth of quartz and feldspar—supposed eutectic proportions—the quartz is high and alkalies are low. The lime and potash, both being low, make the rock resemble bostonite in composition, but it is more quartzose than that type. Winchell[1] has tabulated the terms used in the common qualitative system for the red rocks. Possibly granophyr is appropriate for most of the rock.

Gradation and relations.—In the sill in the eastern part of the city there is a remarkable example of perfect gradation from diabase to red rock. The diabase is of ordinary type, with a finer contact phase at the base. It is exposed almost continuously for a width of a mile, equivalent to a thickness of several hundred feet. The diabase grades up into a red-rock zone of smaller thickness and less regularity, though a belt may be followed several blocks. It is noteworthy that while the sill must be nearly 1,500 feet thick, the conspicuous gradation zone is less than 50 feet, from black diabase to intensely red granophyr.

[1] A. N. Winchell, "Review of Nomenclature of Keweenawan Igneous Rocks," *Jour. Geol.*, XVI (1908), 765–74.

A somewhat different gradation is observed in Lincoln Park and near the top of the inclined railroad to Duluth Heights. In these places it is possible to select samples showing all stages between gabbro and red rock, but the relations are not those of a regular zone. The upper part of the banded gabbro shows many local patches with interstitial red granophyr, grading into dikelike stringers and patches of red rock of complex form and relations (Fig. 7). Many of these stringers with sharply defined walls can be traced along their length into less sharply defined markings and finally grade imperceptibly into the black gabbro which formed the walls a few feet away. Both the gabbro and the red rock intrude the roof, sometimes in the same crack, sometimes more distinctly. Although a considerable part of the red rock is so much later in time of solidification that it could intrude the gabbro, the texture of the red rock is coarse up to its contacts and grades into that of the gabbro without a break, indicating that they were about equally hot. The irregularity in the form of the stringers may also be a sign that the gabbro was not wholly solid (see Fig. 7). Such a relation may be properly described as that of an aplite.

Similar relations of gabbro to red rock, both gradational and aplitic, are easily traced for many miles along the belt at the northeast end of the gabbro in Cook County, where the combined thickness is so reduced as to make the mass more like a sill, and the red rock constitutes a larger proportion of the intrusion than at Duluth. The same relation may be expected in the central, thicker part of the gabbro mass,[1] but this has not been mapped in detail as yet (see Fig. 1).

A third gradation from red rock to gabbro is that in the pegmatites near the base.[2]

Origin of the red rock.—All three of these occurrences of red rock and gradations would seem from field studies to be clearly attributable to a differentiation. However, this sweeping assignment of the granophyr to differentiation ignores a whole group of occurrences

[1] This is not wholly in agreement with the brief statements in *U.S. Geol. Sur. Mon. 52*, pp. 374–75.

[2] Frank F. Grout, "The Pegmatites of the Duluth Gabbro," *Econ. Geol.*, XIII, (1918), 185.

which are characteristic of the contacts of diabase with acid rocks. The association is too striking to be thus ignored. At Duluth the case is illustrated by a very narrow granophyr zone at the base of an extrusive diabase north of Short Line Park, where it overflowed a quartzose sand. Where such flows rest on the other flows no

FIG. 7.—Aplitic stringers of red rock in the Duluth gabbro, near the top

such granophyr has been detected. Again, at Pigeon Point a gabbro seemingly related to the Duluth gabbro has inclusions of quartzite which are characterized by a complete inclosing shell of red rock.[1] The composition of the red rock in these cases is not such as can be derived from the sediment, nor from the average

[1] W. S. Bayley, "The Rocks of Pigeon Point," *U.S. Geol. Surv. Bull. 109*, p. 101; R. A. Daly, "The Geology of Pigeon Point," *Am. Jour. Sci.*, XLIII, 423.

magma, nor any possible mixture. Mr. T. M. Broderick, of Minnesota, has recently checked up the previous work on the chemical nature of the rocks by determining the alkali content of all the rocks at the contact of gabbro with an inclusion of quartzite. If red rock in this situation is derived from quartzite it is derived from the immediately adjacent inclusion. The gabbro has 3.49 per cent alkali and the quartzite 3.60 per cent, but the red rock has more than either, 8.33 per cent. Some differentiation must have occurred in this case, and probably in all similar contacts, many of which have been listed by Bowen.[1]

If it is granted that differentiation occurred, it is easily shown that local assimilation has been relatively slight. The composition of any known differentiate would become evidently hybrid with small additions of the sediments near by.

Deep-seated assimilation and differentiation—syntexis—may have occurred, but there is little evidence that it played much part in forming red rock. There are several examples of assimilation in the gabbro. The quartz gabbro described by Winchell[2] is near an inclusion of quartzite. Similar endomorphic contact effects are exposed in other parts of the gabbro. None of the assimilation phases resembles red rock.

It is therefore maintained that the granites associated with the Duluth gabbro were dependent more on differentiation than on assimilation of acid rocks. The general discussion of the processes by which granites separate from gabbro magma would be mostly theoretical and too long for this paper, but one theory has been forced into prominence by local observations on the gabbro. The several occurrences may all be explained by supposing that the original magma contained some vapors under pressure and that these tended to separate and escape from the main magma, bearing with them those acid, alkaline constituents for which they seem to have a special affinity. The accumulation of a definite upper zone of red rock would then be the result of a quiet rise of the lighter vaporous separate under an impervious roof. The aplitic areas near the top would be similar gravitative separates, disturbed by

[1] N. L. Bowen, "The Gowanda Lake District, Ontario," *Jour. Geol.*, XVIII, 658.

[2] A. N. Winchell, "The Gabbroid Rocks of Minnesota," *Am. Geol.*, XXVI, 348.

some movements at about the time of solidification. The pegmatites and aplites below would be located not so much by gravity as by simple vaporous tension; the lighter separate, being more fluid, might penetrate cracks on any side of the magma chamber in advance of the main magma. The red rock at the borders of siliceous sediments and filling the pores of sandstones as a cement may similarly have escaped from the magma under the tension of the vapors. The position of such a red-rock zone may be determined less by gravity than by porosity. The vaporous solution could escape through the pores in advance of the gabbro. In an extreme case this separation of red rock might even be determined by a porous inclusion. However, the most favorable conditions for the accumulation of red rock must be the combination of a large body of magma with plenty of water and a sandstone roof having a tight cover above.

RELATION OF ROCK TYPES TO POSITION

It is estimated that over two-thirds of the gabbro mass at Duluth consists of olivine gabbro, varying only slightly from the average. Such average rocks are scattered from top to bottom. On the other hand, specialized types have a more limited range. The peridotite occurs only near the base; the magnetite gabbro, equally heavy, is near the center; the anorthite ranges from the center toward the top and is largely in the thin earlier intrusion. Very locally at the base of the early gabbro there is an apatitic hypersthene gabbro. The occurrence of red rock, mostly near the top and in a sill at a higher horizon, is emphasized above.

DIFFERENTIATION

Introduction.—It must be granted, in regard to the Duluth lopolith, that a magma supply was available, and, as indicated by the earlier flows in the same region, it varied from time to time or place to place. The problem of its history as a lopolith begins with its intrusion into the present chamber. Various theories are current as to the processes by which a magma during such a history gives rise to a series of rock types instead of a single one. The roof of the magma for much of its area was diabase and too much like the

magma to indicate that assimilation after intrusion could yield new types. Successive intrusions certainly differed slightly, and it is likely that some parts of the earlier magma were very nearly of the composition of anorthosite. However, although this early magma is different from the later, larger intrusion, there is no sign that the variety in the main gabbro is due to successive intrusions. If this main gabbro was heterogeneous when intruded there was plenty of time for it to become mixed, unless the tendency of the parts was to become more distinct rather than to mix. It therefore seems that the main development of variety in the lopolith depended on processes of differentiation. The variety of rocks described above shows how thorough this differentiation was.

Processes of differentiation.—Recent experimental work is very conclusive in maintaining the reality of crystal settling in a magma and the improbability of extended diffusion as factors in differentiation. It is much less conclusive in dismissing convection and assimilation and the separation of immiscible fractions of magmas.[1] There are some evidences at Duluth which indicate the processes involved.

Crystal settling versus convection.—One of the first considerations in a study of crystal settling concerns the plagioclase. The mass was so large that at Duluth the crystals must have grown very slowly, for the most part too slowly to yield zoned structures. With such very slow cooling a plagioclase would begin to crystallize with a composition much more basic than would be calculated from an average of the magma; but as crystallization proceeded it might have readjusted itself to the magma, so changed in composition as finally to be the plagioclase indicated by the composition of the average magma. This adjustment is supposedly interfered with in cases of very slow cooling, hence to be expected at Duluth, by the settling or floating of the early basic crystals out of reach of the residual liquid. The crystals should then be more basic plagioclase wherever the early crystals accumulated and more acid elsewhere.[2] Let us see how the Duluth gabbro fits the case.

[1] N. L. Bowen, "Later Stages in the Evolution of Igneous Rocks," *Jour. Geol.*, XXIII (1915), supplement to the December number.

[2] F. L. Bowen, *ibid.*, p. 33.

Nearly all the feldspar of the gabbro, through a thickness of three miles, is basic labradorite or acid bytownite, with surprisingly little variation and no apparent relation between position and the slight variations found. Near the top for a few feet the feldspars are zoned, and directly above is the red rock in small amount. Can 15,000 feet of bytownite, Ab_1An_2, settle out of a magma of more acid composition without changing the composition of the residual liquor, so as to produce a notable change in the crystals forming? And, if so, can 15,000 feet of bytownite, Ab_1An_2, settle from a mother liquor that amounts to less than 300 feet of acid andesine? It is evidently absurd to think that the main gabbro settled, leaving a mother liquor of red rock in such small amount. The gabbro feldspars are too uniform. The early crystals, which were very basic according to theory, forming from a labradorite melt, must have remained in contact with the mother liquor until equilibrium was established and they became average in composition. The crystals may have settled a little, but the viscous magma more than likely moved with them in convection most of the way. The end of crystallization came when the crystals lodged in the more viscous wall or floor, and there slowly, maintaining equilibrium, the crystals adjusted their composition to that of the magma around them, some bytownite, some labradorite.[1]

In connection with crystal settling the gravitative position of differentiates is cited as strong confirmation. The Duluth gabbro is supposed to be one of the best illustrations, since it is commonly thought that magnetite separated at the base. As a fact, the segregated ores are far from the base; the best concentrations are bands centrally placed in banded gabbro. Ores near the base are contact ores or xenoliths, and the gabbro at the base shows very

[1] The mechanics of the convection has been outlined elsewhere. See Frank F. Grout, "Two-Phase Convection in Igneous Magmas," *Jour. Geol.*, XXVI (1918), 481.

Another more general criticism of crystal settling may be noted at this time. Bowen records in the *Am. Jour. Sci.*, XXXIX, 175, that crystals grow during settling in a crucible from an infinitesimal start to one-tenth of a millimeter, in settling 15 millimeters. How far-fetched it is then to think of the grains of common igneous rocks as having settled thousands of feet in a laccolith or batholith! Crystal settling is an idea to think of in terms of a few feet rather than in hundreds of feet.

little enrichment in magnetite.[1] Weinschenk is authority for the statement that this is a general rule in the segregation of magnetite.[2]

Fig. 8 shows the specific gravities of the rocks of which there are data in their "stratigraphic" sequence. A curve has been drawn to indicate in a greatly generalized way the decrease in

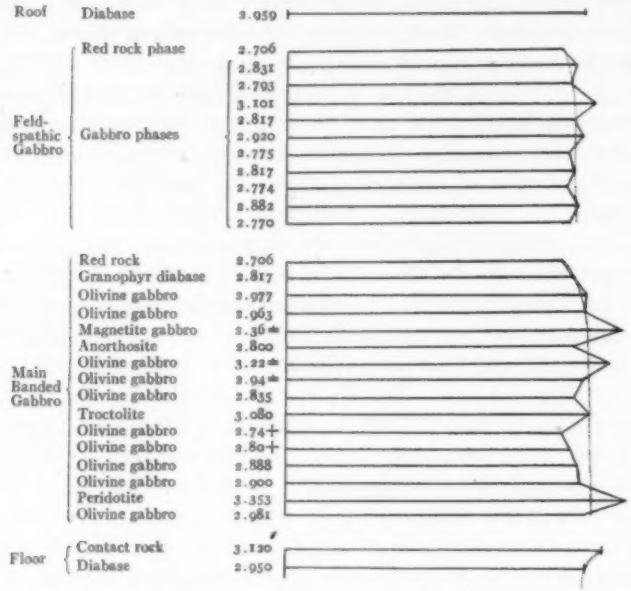

FIG. 8.—Specific gravities of Duluth rocks in "stratigraphic" order

specific gravity toward the top of the mass at Duluth, but when the data are studied in detail it is found that the curve is hardly justified. One of the heaviest rocks found was well above the center. It is thought that many of the cited examples of gravitative arrangement will show in detail the same erratic curve.

How is this irregular specific-gravity series explained? The idea of crystal settling has not been so stated as to cover it. The

[1] T. M. Broderick, "The Relation of the Titaniferous Magnetites of Northeastern Minnesota to the Duluth Gabbro," *Econ. Geol.*, XII (1917), 663.

[2] Dr. E. Weinschenk, translation by A. Johannsen, "The Fundamental Principles of Petrology." McGraw-Hill Co. (1916), p. 45.

idea of convection with a rhythm of crystallization would lead one to expect exactly what is here found.[1] The first crystals to form, if not altogether too light, would be the first to drag along the bottom. The heavy minerals would take their turn, and the magnetite being, at least partly, later in time of crystallization would remain liquid until the lower parts of the chamber were filled with layers of rock. Thus both the uniform feldspar and the curve of gravity may be taken as signs of convection.

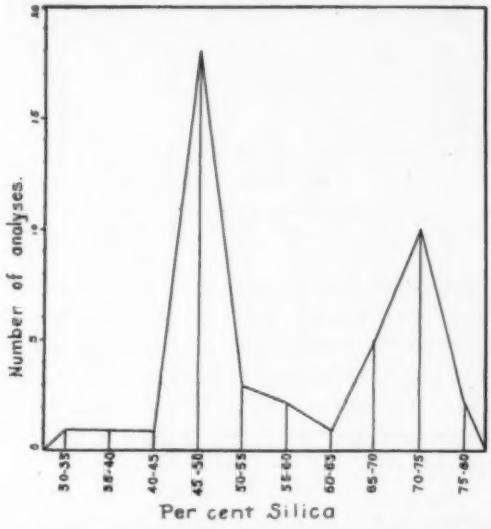

FIG. 9.—Silica content of specimens of the Duluth gabbro formation

Double differentiation.—A second feature of the rocks of the lopolith, which has a bearing on the process of differentiation, is the apparent break in the series. This is evident in plotting curves of variation in chemical or mineralogic constituents, and even more strikingly in a mathematical arrangement of the quantitative classification. Nothing in the outline of crystallization differentiation leads one to expect any sudden changes in rock types or any omissions in the series of intermediate rocks. A mass of rock with

[1] Frank F. Grout, "Two-Phase Convection in Igneous Magmas," *Jour. Geol.*, XXVI (1918), 481.

alkali feldspar is derived from gabbro only when a similar or larger amount of rock has separated with a medium to acid labradorite or andesine. No such rock is known at Duluth, though the small transition zones do exhibit zoned feldspars.

The arrangement of analyses according to the per cent of silica shows two well-defined and separated groups, one about 47 per cent silica and one about 72 per cent silica (see Fig. 9). The groups are evidently related to the two groups distinguished as gabbro and red rock. All the red rock contains more than 57 per cent silica;

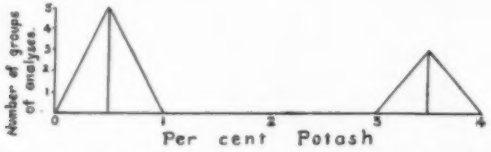

FIG. 10.—The potash content of the Duluth gabbro formation, as shown by available analyses (in groups).

no gabbro has as much as 57 per cent. The break appears even more sharply when the analyses are arranged in the order of silica per cent and a curve is drawn for the per cent of potash (see Fig. 10). All the groups of red rock analyses have more than three per cent of potash, while the gabbro groups all have less than 1 per cent. Although single analyses may show exceptional figures there is no real overlap.[1]

Silica per cent	Potash per cent: In detail	Potash per cent: By groups	
2.02	0		
32.90	0+	0.17	
35.81	0.33		
42.24	0.27		
45.65	1.05		
45.66	0.41		
46.45	0.34	0.56	
47.05	0.05		
47.10	0.92		
47.25	0.37		
47.79	0.53		
47.90	0.56	0.66	Gabbro
48.20	0.32		
49.13	1.01		
49.18	0.82		
49.39	0.10		
49.42	1.15	0.71	
49.78	0.46		
49.88	0.68		
50.43	0.34		
50.86	0.90		
52.48	1.75	0.95	
53.43	1.12		
56.60	0.45		

Silica per cent	Potash per cent: In detail	Potash per cent: By groups	
57.98	3.44		
61.09	3.05		
65.56	2.88	3.20	
66.36	3.05		
66.92	3.98		
68.36	4.48		
71.13	2.40		
71.81	1.92	3.66	Red rock
72.42	4.97		
73.28	4.50		
73.70	4.56		
73.91	2.78	3.18	
74.00	4.33		
75.78	1.06		

It is not suggested for a moment that the series at Duluth does not include all types in complete gradation, but the gradation zone is small, and the separation of two types is very complete. Even though some samples were selected to show intermediate rocks, the analyses show that they belong distinctly to one side or the other of a break in the series.

When these sharply divided groups are studied in detail, each is found to vary widely without crossing the limits of the group to

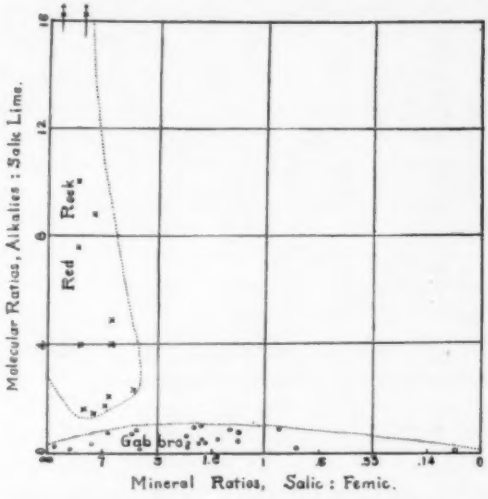

FIG. 11.—Diagram based on Duluth analyses, showing that the variation in the gabbro is in a different direction from the variation in the red rock. While the gabbro varies from salic to femic, it never becomes alkalic. While the red rock varies from alkalic to calcic, it nowhere becomes femic.

approach the other. There is no way to arrange all the gabbros in a single linear series, but this complexity in the gabbro group is entirely aside from the series grading toward red rock. It is a gradation of a really different character (see Fig. 11).

One series of rocks from peridotite to olivine gabbro and anorthosite, with some side branches to magnetitic gabbro and troctolite, varies chiefly in the quantities of minerals—labradorite, augite, olivine, and magnetite. In the main course of variation all four

gabbro minerals are present and the composition of minerals is surprisingly uniform throughout. When any mineral differs from the average the variation is not visibly related to the position or to the associated minerals.

A second type of variation is that from the general gabbro type to the granophyr. This is a change in mineral composition as well as a change in the essential minerals present (see Fig. 12). In the field this change comes with surprising abruptness, after the

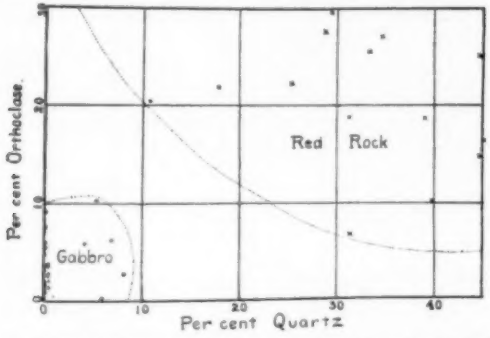

FIG. 12.—Diagram showing the break between gabbro and red rock at Duluth when plotted on the basis of quartz and orthoclase content.

monotony of slightly varying gabbro bands, with an extreme only occasionally. In a few feet after the reddish tinge of granophyr is seen in the interstices of the gabbro none of the gabbro minerals are visible in the rock.

This double process is distinctly contrary to the idea of Bowen's paper, and there are few suggestions of the sort in the literature. There are, indeed, suggestions of different types of differentiation. Bowen outlines two series from gabbro to alkaline types.[1] Harker has contrasted regional and local action.[2] Lane speaks of wet and dry differentiation.[3] However, there is evidence at Duluth of two

[1] N. L. Bowen, "Later Stages in the Evolution of Igneous Rocks," *Jour. Geol.*, XXIII (1915), December Supplement, p. 77.

[2] A. Harker, "Tertiary Igneous Rocks of Skye," *Mem. Geol. Survey of the United Kingdom* (1904), p. 419.

[3] A. C. Lane, "Wet and Dry Differentiation," *Tufts College Studies*, III, 39.

contrasting series in a single mass cooling in a single chamber, and a study of the literature of other districts makes it seem likely that this double sequence is a common thing.

The association of both granophyr and anorthosite as differentiates of normal gabbro is too common to have escaped observation. Each rock requires large bodies of magma for its production and each is of low specific gravity. Several geologists discuss these rocks as normal differentiates of gabbro, but no one has developed a satisfactory explanation of the manner in which the two rocks form. To be sure, a line of descent can be stated so that both are mentioned, but the suggested origin would lead one to expect them in very different field relations from those at Duluth. Thus, when peridotite, troctolite, and olivine gabbro had separated from the magma, the feldspar should begin to grow more acid and the olivine less abundant; but no such relation appears. Later, considerable magma of dioritic composition might yield crystals of gabbroic nature while itself as a liquid approaching the composition of a granite. However, before it reaches the composition of such a granophyr as the red rock of Duluth a large amount of feldspar must have crystallized from a magma too acid to yield basic labradorite; that is, at some stage, a quantity of diorite and granodiorite must have separated. No such rocks appear. Instead, there is a very narrow zone of granophyr diabase, in which the feldspars, to be sure, are zoned according to theory; but the zone is too small to yield the masses of red granophyr actually found.

Thus the characteristic rock series at Duluth is neither of Bowen's recognized series:[1] "gabbro, diorite, quartz diorite, granodiorite, granite"; nor "gabbro, diorite, syenite, granite." The series is rather (1) gabbro, (2) granophyr diabase, (3) granite, with the second member very small in bulk. This is believed to be a common sequence. Harker recently called attention to the general lack of intermediate rocks in such rock masses.[2]

[1] *Loc. cit.*

[2] A. Harker, "Differentiation in Intercrustal Magma Basins," *Jour. Geol.*, XXIV, 554.

TABLE I

Chemical Analyses—Gabbro from Duluth

	1	2	3	4	5	6	7	8	9*	10	11
Silica SiO_2	48.20	32.90	49.30	47.10	42.24	35.81	52.48	45.65	49.15	49.42	50.43
Alumina Al_2O_3	19.53	1.59	29.08	12.92	18.50	14.32	15.47	15.20	21.90	24.47	23.83
Ferric oxide Fe_2O_3	Trace	13.25	0.34	12.95	4.68	7.38	5.14	6.71	6.60	3.13	17.63
Ferrous oxide FeO	10.60	21.06	2.89	9.46	14.50	15.25	9.25	13.81	4.54	6.15	
Magnesia MgO	9.28	20.14	2.26	3.08	2.76	10.49	2.55	2.95	3.03	1.00	2.46
Lime CaO	8.51	0.50	13.06	10.29	10.36	7.23	7.27	6.33	8.22	8.45	4.79
Soda Na_2O	2.52	Trace	2.89	2.61	2.19	2.06	3.26	3.09	3.83	4.98	2.06
Potash K_2O	0.32	Trace	0.10	0.92	0.33	0.37	1.75	1.05	1.61	1.15	0.34
Combined water H_2O+	0.65	4.56	0.34	0.71	1.80	5.25	1.24	2.29	1.92	0.55	.....
Moisture H_2O-	0.08	0.55	0.09	0.12	0.25	.....	.....	.....	.....	0.00	.....
Carbon dioxide CO_2	0.02	0.10	Trace	.....	1.67	Traces	.....	.....	.....	.....	.....
Titania TiO_2	0.65	5.36	Trace	1.38	1.16	2.30	1.26	1.66	0.18	1.87	Trace
Phosphorus oxide P_2O_5	0.19	Trace	0.09	0.01	0.19	.....	0.29	0.25	0.33	0.04	.....
Sulphur S	0.03	0.05	None	.....	.....	.....	.....	.....	.....	0.11	.....
Chromium oxide Cr_2O_3	Trace	0.04	Trace	.....	.....	.....	.....	.....	.....	.....	.....
Copper oxide Cu_2O	.....	0.15	.....	.....	.....	.....	.....	.....	.....	.....	.....
Manganous oxide MnO	0.14	0.40	0.04	0.80	0.13	0.18	0.51	0.71	.....	0.11	.....
Rarer elements	Trace	0.06	None	.....	.....	.....	Traces	Traces	.....	.....	.....
	100.72	100.71	100.57	101.63	100.76	100.62	100.47	99.70	100.80*	101.48	101.54
Specific gravity	2.963	3.353	2.770	.....	.....	3.07–3.10	2.81–2.84	2.84–2.86	.....	.....	2.79–2.802

* Original summation did not include P_2O_5 and TiO_2.

TABLE I—*Continued*

NORMS AND CLASSIFICATION

	1	2*	3	4*	5	6	7	8	9	10	11†
Quartz	.....	.....	.....	.....	.....	.....	5.6	.....	.....	.....	.....
Orthoclase	1.67	.....	0.56	5.56	1.67	2.22	10.6	6.1	9.45	7.23	.....
Albite	21.48	.....	24.63	22.01	18.34	7.86	27.2	26.2	31.96	32.49	.....
Anorthite	40.59	2.50	63.94	20.57	39.75	28.63	22.5	24.5	38.09	40.59	.....
Nephelite	.....	.....	.....	.....	.....	5.11	.....	.....	.....	5.40	.....
Corundum	.....	.....	0.71	.....	.....	.....	.....	.....	.....	.....	.....
Diopside	0.68	10.88	.....	26.16	9.28	5.91	11.4	5.2	0.68	1.18	.....
Hypersthene	12.54	4.85	6.34	9.26	4.27	.....	11.6	19.5	4.16	.....	.....
Olivine	21.20	62.60	3.14	5.34	14.24	30.41	.....	1.7	4.12	11.79	.....
Magnetite	.....	0.93	0.46	12.02	0.73	10.67	7.4	9.7	9.51	4.41	.....
Ilmenite	1.22	8.43	.....	2.74	2.28	4.41	2.4	3.2	0.30	3.50	.....
Apatite	0.34	.....	0.34	.....	.34	.....	.5	.5	.67	.....	.....
	Dosalic Perfelic Docalcic Persodic	Perfemic (Perfelic) (Docalcic)	Persalic Perfelic Docalcic Persodic	Salfemic Perfelic Alkalicalcic Dosodic	Salfemic Perfelic Docalcic Persodic	Salfemic Perfelic Docalcic Persodic	Dosalic Perfelic Alkalicalcic Dosodic	Salfemic Perfelic Alkalicalcic Dosodic	Dosalic Perfelic Docalcic Dosodic	Dosalic Perfelic Alkalicalcic Dosodic	(Persalic) (Dofelic) (Docalcic) (Persodic)
	Hessose II.5.4.5	..... V.5.4.–	Labradorose I.5.4.5	Camptonose III.5.3.4	Auvergnose III.5.4.5	Auvergnose III.5.4.5	Andose II.5.3.4	Camptonose III.5.3.4	Hessose II.5.4.4	Andose II.5.3.4	.....

* Estimate based on the known secondary oxidation of part of the iron.

† "Not good for classification." H.S.W., PP 14, p. 431.

1. Olivine Gabbro. Sec. 23, T. 49 N., R. 15 W., West Duluth. F. F. Grout.
2. Peridotite. Sec. 34, T. 49 N., R. 15 W., Short Line Park. F. F. Grout.
3. Anorthosite. Sec. 19, T. 50 N., R. 14 W., North of Proctor. F. F. Grout
4. Olivine Gabbro. Sec. 33, T. 49 N., R. 15 W., Short Line Park. G. S. Nishihara.
5. Gabbro Pegmatite. Sec. 33, T. 49 N., R. 15 W., Short Line Park. G. S. Nishihara
6. Troctolite. Sec. 22, T. 50 N., R. 15 W., North of Proctor. A. N. Winchell. *Am. Geol.*, XXVI, 284.
7. Orthoclase Gabbro. Down town at Duluth. A. N. Winchell. *Am. Geol.*, XXVI, 293.
8. Hornblende Orthoclase Gabbro. Down town at Duluth. A. N. Winchell. *Am. Geol.*, XXVI, 293.
9. Hornblende Gabbro. At Duluth. A. Streng. *Neues Jahrbuch für Mineralogie, Geologie und Paleontologie*, 1877, p. 113.
10. Gabbro, probably of the feldspathic type. Near the center of Sec. 33, T. 50 N., R. 14 W., Duluth. G. H. Stone. *Jour. Geol.*, XVIII, 656.
11. Gabbro, feldspathic type. Sec. 34, T. 50 N., R. 14 W., Duluth. J. A. Dodge. *Minn. Geol. and Nat. Hist. Survey, Final Rep.*, V, 85.

TABLE I—*Continued*

ANALYSES OF DULUTH GABBRO, NORTHEAST OF THE TYPE LOCALITY

	12	13	14	15	16	17	18
Silica SiO_2	2.02	45.66	46.45	47.70	47.90	53.43	56.60
Alumina Al_2O_3	2.68	16.44	21.30	19.04	19.92	13.81	17.84
Ferric oxide Fe_2O_3	80.78	0.66	0.81	0.87	4.92	5.08	2.55
Ferrous oxide FeO		13.90	9.57	8.84	9.78	9.86	4.09
Magnesia MgO		11.57	7.90	8.65	4.55	4.64	3.16
Lime CaO	Trace	7.23	9.83	8.96	8.56	8.25	6.28
Soda Na_2		2.13	2.14	2.53	2.75	2.51	4.45
Potash K_2O		0.41	0.34	0.53	0.56	1.12	0.45
Combined water H_2O+		0.83	1.02	1.38	0.76	0.27	3.20
Moisture H_2O-		0.07	0.14				
Carbon dioxide CO_2				Trace	n.d.		n.d.
Titania TiO_2	12.09	0.92	1.19	1.80	0.57		1.59
Phosphorus oxide P_2O_5	0.03	0.05	0.02	n.d.	n.d.		0.14
Chromium oxide Cr_2O_3	2.40	Trace					
Manganous oxide MnO		Trace	Trace	Trace		Trace	
Nickel oxide NiO		0.16	0.04				
Other elements				Traces	Traces		Traces
	99.90	100.03	100.75	100.30	100.27	98.97	100.35
Specific gravity				2.89	2.93		2.38*

* Evidently an error but correctly quoted.

TABLE I—*Continued*

NORMS AND CLASSIFICATION

	12	13	14	15	16	17	18
Quartz						7.68	8.9
Orthoclase		2.2	1.7	2.8	3.3	6.67	2.8
Albite		17.8	17.8	21.0	23.1	20.96	37.7
Anorthite		34.2	47.8	39.2	40.0	23.07	27.2
Diopside		1.4	0.8	4.5	2.0	14.78	3.4
Hypersthene		10.1	11.1	12.7	19.8	18.10	11.5
Olivine		30.3	16.8	13.9	1.8		
Magnetite	95.27	0.9	1.2	1.4	7.2	7.42	3.7
Ilmenite		2.6	2.3	3.4	1.1		3.1
Apatite							
	Perfemic (Perfelic)	Salfemic Perfelic	Dosalic Perfelic	Dosalic Perfelic	Dosalic Perfelic	Salfemic Dofelic	Dosalic Perfelic
	.....	Docalcic	Docalcic	Docalcic	Docalcic	Docalcic	Alkalicalcic
	.....	Persodic	Persodic	Persodic	Persodic	Dosodic	Persodic
	X	Auvergnose	Hessose	Hessose	Hessose	X	Beerbachose
	V.5—	III.5.4.5	II.5.4.5	II.5.4.5	II.5.4.5	III.4.4.4	II.5.3.5

12. Gabbro magnetite. On the south side of Iron Lake, Sec. 36, T. 65 N., R. 3 W. R. S. Robertson. *Minn. Geol. and Nat. Hist. Survey Bull. 6*, p. 141.
13. Gabbro. Sec. 19, T. 63 N., R. 9 W. H. N. Stokes. *Jour. Geol.*, I, 712.
14. Gabbro, representative. Sec. 35, T. 61 N., R. 12 W. H. N. Stokes. *Jour. Geol.*, I, 712.
15. Olivine Gabbro. Birch Lake. H. N. Stokes. *Am. Geol.*, XXVI, p. 181.
16. Diabase Gabbro. East side of Birch Lake. A. N. Winchell. *Am. Geol.*, XXVI, 374.
17. Gabbro with quartz. Endomorphic contact rock. Sec. 11, T. 63 N., R. 5 W. Dodge and Sidener. *Minn. Geol. and Nat. Hist. Survey, Final Rep.* V, 543.
18. Quartz Gabbro. Sec. 12, T. 64 N., R. 6 W. Little Saganaga Lake. A. N. Winchell. *Am. Geol.*, XXVI, p. 352.

TABLE I—*Continued*

ANALYSES OF SILLS AND MASSES SUPPOSED TO BE RELATED TO THE DULUTH GABBRO

	19	20	21	22	23	24
Silica SiO_2	49.18	49.88	50.86	47.25	49.78	47.05
Alumina Al_2O_3	19.01	18.55	15.72	31.56	29.37	32.03
Ferric oxide Fe_2O_3	0.89	2.06	9.77	.....	0.34	2.01
Ferrous oxide FeO	7.79	8.37	2.48	2.29	0.60	
Magnesia MgO	6.48	5.77	3.55	0.27	1.07	0.15
Lime CaO	9.12	9.70	10.52	15.39	11.86	15.85
Soda Na_2O	3.32	2.50	3.89	2.52	4.39	1.00
Potash K_2O	0.82	0.68	0.90	0.37	0.46	0.05
Combined water H_2O+	2.06	1.04	2.53	0.40	1.76	1.36
Moisture H_2O-	.....	.....	.....	.....	.....	.....
Carbon dioxide CO_2	Trace	.....	.....	.....	.....	.....
Titania TiO_2	1.09	1.19	.....	.....	None	.....
Phosphorus oxide P_2O_5	.....	0.16	.....	.....	Traces	.....
Manganous oxide MnO	0.31	0.09	.....	.....	0.08	.....
Barium oxide BaO	None	0.02	.....	.....	None	.....
Other elements	Traces	.....	.....	.....	Traces	.....
	100.21	100.21	100.22	100.05	99.80	99.50
Specific gravity	2.84	2.923–2.970	.....	About 2.7	2.676	.....

TABLE I—*Continued*

ANALYSES OF RED-ROCK INTRUSIVES AT DULUTH

	25	26	27	28
Silica SiO_2	66.92	66.36	75.78	65.56
Alumina Al_2O_3	12.51	13.33	11.09	10.06
Ferric oxide Fe_2O_3	4.36	7.89	2.09	14.40
Ferrous oxide FeO	3.93	2.96	.....	0.23
Magnesia MgO	1.66	1.20	0.65	0.73
Lime CaO	1.90	2.14	0.86	0.96
Soda Na_2O	3.45	2.63	6.43	2.25
Potash K_2O	3.98	3.05	1.06	2.88
Combined water H_2O+	1.35	1.21	1.82	0.86
Moisture H_2O-	0.20	.....	.....	.....
Carbon dioxide CO_2	0.02	.....	.....	.....
Titania TiO_2	0.69	.....	.....	.....
Zirconia ZrO_2	0.22	.....	.....	.....
Phosphorus oxide P_2O_5	0.11	.....	.....	.....
Sulphur S	0.04	.....	.....	.....
Manganous oxide MnO	0.16	.....	.....	.....
Barium oxide BaO	0.06	.....	.....	.....
	100.76	100.77	99.78	97.93
Specific gravity	2.721	.....	.....	.....

TABLE I—*Continued*

NORMS AND CLASSIFICATION

	19	20	21	22	23	24
Quartz	.....	.....	3.2	.....	.....	6.60
Orthoclase	5.00	3.9	5.6	2.22	2.8	.....
Albite	27.77	22.0	33.0	15.20	28.8	8.38
Anorthite	34.47	37.0	22.5	73.40	58.7	78.68
Nepheline	.....	.....	.....	3.41	4.5	.....
Corundum	.....	.....	.....	.....	.....	1.53
Diopside	8.90	8.9	19.3	2.67	.....	.....
Hypersthene	2.76	21.8	.....	.....	.....	1.46
Olivine	15.74	.....	.....	2.70	2.5	.....
Magnetite	1.39	3.0	8.1	.....	0.5	1.39
Ilmenite	2.13	2.3	.....	.....	.....	.....
Hematite	.....	.....	4.2	.....	.....	.....
Wollastonite	.....	.....	2.0	.....	.....	.....
	Dosalic Perfelic Docalcic Dosodic	Dosalic Perfelic Docalcic Dosodic	Dosalic Perfelic Alkalicalcic Dosodic	Persalic Perfelic Docalcic Persodic	Persalic Perfelic Docalcic Persodic	Persalic Perfelic Percalcic Persodic
	Hessose	Hessose	Andose	Labrador-rose	Labrador-rose	Persodic Canadase
	II.5.4.4	II.5.4.4	II.5.3.4	I.5.4.5	I.5.4.5	I.5.5.5

19. Olivine diabase. Pigeon Point. A. N. Winchell. *Am. Geol.*, XXVI, 213.
20. Olivine gabbro. Pigeon Point. W. F. Hillebrand. *U.S. Geol. Survey Bul. 109*, p. 63.
21. "Altered Gabbro. East of Baptism River." Dodge and Sidener. This probably is "Beaver Bay diabase." *Minn. Geol. and Nat. Hist. Survey Bul. 2*, p. 79.
22. Anorthosite. At mouth of Split Rock River, quoted from R. D. Irving. *U.S. Geol. Survey Mon.*, V, p. 438.
23. Anorthosite. Carlton Peak. A. N. Winchell. *Am. Geol.*, XXVI, 281.
24. Anorthosite. At the foot of Caribou Peak. C. F. Sidener.

TABLE I—*Continued*

NORMS AND CLASSIFICATION

	25	26	27	28
Quartz	25.50	33.00	33.00	38.28
Orthoclase	23.91	17.79	6.67	17.24
Albite	28.89	22.53	50.83	18.86
Anorthite	5.28	10.56	.....	4.73
Corundum	0.61	1.73	.....	1.53
Zircon	0.37	.....	.....	.....
Diopside	.....	.....	3.24	.....
Hypersthene	6.87	3.00	0.10	1.80
Acmite	.....	.....	3.23	.....
Magnetite	6.26	9.51	.....	0.93
Ilmenite	1.37	.....	.....	.....
Hematite	.....	1.28	0.96	13.76
Apatite	0.34	.....	.....	.....
	Dosalic Dofelic Domalkalic Sodipotassic	Dosalic Quarfelic Domalkalic Sodipotassic	Persalic Dofelic Peralkalic Persodic	Dosalic Quarfelic Domalkalic Sodipotassic
	Adamellose	X	Noyangose	X
	II.4.2.3	II.5.2.3	I.4.1.5	II.3.2.3

25. Red Rock. N.W. corner Sec. 27, T. 50 N., R. 14 W. F. F. Grout.
26. Red Granite. Rice's Point, Duluth. J. A. Dodge. *Minn. Geol. and Nat. Hist. Survey, 13th Ann. Rep.*, p. 100.
27. Red Granite. Rice's Point, Duluth. J. A. Dodge. *Minn. Geol. and Nat. Hist. Survey, 10th Ann. Rep.*, p. 204.
28. Red Granite. East of Lester River, East Duluth. J. A. Dodge. *Minn. Geol. and Nat. Hist. Survey, 13th Ann. Rep.*, p. 100.

TABLE I—*Continued*

ANALYSES OF RED-ROCK INTRUSIVES NORTHEAST OF DULUTH SUPPOSED TO BE RELATED TO THE DULUTH GABBRO

	29	30	31	32	33	34	35	36	37	38
Silica SiO_2	57.98	61.09	68.36	72.42	74.00	73.91	73.70	71.15	71.81	73.28
Alumina Al_2O_3	13.58	15.34	13.76	13.04	12.04	14.89	12.87	12.40	12.82	11.83
Ferric oxide Fe_2O_3	3.11	5.74	2.65	0.68	0.78	2.27	3.76	5.21	6.02	4.61
Ferrous oxide FeO	8.68	3.69	2.75	2.49	2.61	1.70	0.31	0.75		0.56
Magnesia MgO	2.87	1.33	0.68	0.58	0.42	Trace	0.11	1.13	0.56	0.36
Lime CaO	2.02	3.10	0.70	0.66	0.85	0.27	0.14	1.90	2.26	1.04
Soda Na_2O	3.56	3.41	3.56	3.44	3.47	2.64	3.63	1.70	2.51	1.66
Potash K_2O	3.44	3.65	4.48	4.97	4.33	2.78	4.56	2.40	1.92	4.50
Combined water H_2O+	2.47	1.80	0.98	1.21	0.80	1.01	0.57	2.12	.....	1.82
Moisture H_2O-	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Titania TiO_2	1.75	.....	1.57	0.40	0.34	.....	0.12	.....	.....	.....
Phosphorus oxide P_2O_5	0.29	.....	0.33	0.20	0.06	.....	Trace	.....	.....	.....
Sulphuric oxide SO_3	.....	.....	0.66	.....	.....	.....	.....	.....	.....	.....
Manganous oxide MnO	0.13	.....	.....	0.09	0.05	.....	0.07	.....	.....	.....
Barium oxide BaO	0.04	.....	.....	0.15	0.13	.....	.....	.....	.....	.....
Other elements	Traces	.....	.....	Traces	Traces	.....	.....	.....	.....	.....
	99.91	99.15	100.48	100.37	99.93	99.47	99.84	98.76	97.90	99.66
Specific gravity	.....	.....	.....	2.620	2.565	.....	.....	.....	.....	.....

TABLE I—*Continued*

NORMS AND CLASSIFICATION

	29	30	31	32	33	34	35	36	37	38
Quartz	11.1	17.7	28.0	29.4	33.2	46.44	34.7	45.12	40.08*	43.44
Orthoclase	20.0	21.2	26.7	30.0	25.6	16.68	27.2	14.46	11.12	26.69
Albite	29.9	28.8	29.9	28.8	29.3	22.53	30.4	14.15	20.96	14.15
Anorthite	10.0	15.3	3.3	3.2	4.2	1.39	0.6	9.45	11.12	5.28
Corundum	0.5	.....	1.8	0.8	.....	6.94	1.7	3.57	2.55	2.24
Hypersthene	17.7	5.4	1.9	5.0	4.6	1.32	0.3	2.80	11.30	0.90
Magnetite	8.0	8.1	3.9	0.9	1.2	3.25	0.9	2.55	.....	1.87
Ilmenite	3.4	.....	3.1	0.8	0.6	.....	.....	.....	.....	.....
Hematite	.....	.....	.....	.....	.....	.....	3.2	3.52	.....	3.36

* Assuming that some ferric iron is secondarily oxidized, as is evident.

Dosalic Dofelic Domalkalic Sodipotassic	Dosalic Dofelic Domalkalic Sodipotassic	Persalic Dofelic Peralkalic Sodipotassic	Persalic Dofelic Peralkalic Sodipotassic	Persalic Dofelic Domalkalic Sodipotassic	Persalic Quarfelic Peralkalic Sodipotassic	Persalic Dofelic Peralkalic Sodipotassic	Persalic Quarfelic Alkalicalcic Sodipotassic	Persalic Quarfelic Alkalicalcic Dosodic	Persalic Quarfelic Domalkalic Dopotassic
Adamellose	Adamellose	Liparose	Liparose	Toscanose	Alaskose	Liparose	Riesenose	Dosodic Riesenase	Mihalose
II.4.2.3	II.4.2.3	I.4.1.3	I.4.1.3	I.4.2.3	I.3.1.3	I.4.1.3	I.3.3.3	I.3.3.4	I.3.2.2

29. "Intermediate rock," selected to show the type of rock between gabbro and red rock. Pigeon Point. W. F. Hillebrand. *U.S. Geol. Survey Bull. 109*, p. 63.
30. Red Granite. Pigeon Point. M. E. Wadsworth. *Minn. Geol. and Nat. Hist. Survey, Final Rep.*, V, p. 303.
31. Red Rock. Pigeon Point. J. E. Whitfield. *U.S. Geol. Survey Bull. 109*, p. 90.
32. Red Rock. Pigeon Point. W. F. Hillebrand. *U.S. Geol. Survey Bull. 109*, p. 56.
33. Red Rock, porphyritic. Pigeon Point. W. F. Hillebrand. *U.S. Geol. Survey Bull. 109*, p. 56.
34. Red Rock. Island south of Pigeon Point. J. A. Dodge. *Minn. Geol. and Nat. Hist. Survey, 13th Ann. Rep.*, p. 100.
35. Red Rock, porphyritic. Little Brick Island off Pigeon Point. L. G. Eakins. *U.S. Geol. Survey Bull. 109*, p. 58.
36. Granite, pink. West side of Beaver Bay. J. A. Dodge. *Minn. Geol. and Nat. Hist. Survey, 13th Ann. Rep.*, p. 100.
37. Granite, purplish gray. West side of Beaver Bay. J. A. Dodge. *Minn. Geol. and Nat. Hist. Survey, Final Rep.*, V, 400.
38. Red Granite. Third island east of Beaver Bay. J. A. Dodge. *Minn. Geol. and Nat. Hist. Survey, 13th Ann. Rep.*, p. 100.

TABLE II

Classification of Igneous Rock Series from Several Districts

Duluth	Skye	Sudbury	Purcell	Carrock Fell	Preston	Juliana-haab	Sweden	Palisades	Gowganda	St. Davids Head	Adiron-dacks	Cortlandt
Gabbro Series	Diabase and Dolerite	Diabase and Norite	Diabase Sills	Gabbro	Gabbros		Olivine-Diabase, Peridotite, Anorthosite and Iron Ores	Diabase	Sills of Gabbro and Granophyr-Diabase	Various Gabbros	Gabbros, Anorthosite and Iron Ore	Diorite, Gabbro, Norite, Pyroxenite
I.5.4.5											I.5.4.5	
I.5.4.5												
I.5.4.5												
I.5.5.5												
									II.5.2.5			
							II.5.3.3					II.5.3.3
II.5.3.4							II.5.3.4					II.5.3.4
II.5.3.4												II.5.3.4
II.5.3.4												II.5.3.4
II.5.3.5									II.5.3.5	II.5.3.5		
		II.5.4.3									II.5.4.3	II.5.4.3
											II.5.4.3	II.5.4.3
II.5.4.4	II.5.4.–	II.5.4.4					II.5.4.4					
II.5.4.4		II.5.4.4										
II.5.4.4												
II.5.4.5	II.5.4.5			II.5.4.5								
II.5.4.5	II.5.4.5											
II.5.4.5	II.5.4.5											
II.5.4.5												
	II.5.5.5					II.6.1.4						
III.5.3.4			III.(4)(5).5.4			II.7.1.4			III.5.2.4			
III.5.3.4								III.5.3.4		III.5.3.4	III.5.3.4	
								III.5.3.4			III.5.3.4	
								III.5.3.4				
					III.5.3.5			III.5.4.4		III.5.4.4		
			III.5.4.4				III.5.4.4	III.5.4.4				
III.5.4.5			III.5.4.5		III.5.4.5			III.5.4.4				
III.5.4.5					III.5.4.5			III.5.4.4				
III.5.4.5								III.5.4.5				
		III.5.5.5						III.5.4.5				
						III.6.1.3						III.6.3.4
	IV.5.4.4						IV.5.4.4	IV.5.4.4			IV.5.4.3	IV.5.3.3
							IV.5.4.4	IV.5.4.4				IV.5.3.4
											IV.5.–.–	IV.5.3.4
											IV.6.4.4	
V.5.4.–	V.5.4.4											
V.5.–.–												

			Intermediate Rock				Monzonite					
			II.4.4.3				II.4.3.4					
Red Rock	Granophyr	Syenite and Granite	Granite		Oligoclase Granite		Granite	Granophyr-Diabase	Aplite	Aplite	Granite and Syenite	Granite
I.3.1.3									I.3.1.5		I.3.1.3	
I.3.2.2			I.3.2.3		I.3.2.4							
I.3.3.3												
I.3.3.4		I.4.1.2					I.4.1.3					
I.4.1.3										I.4.1.4		
I.4.1.5				I.4.1.4							I.4.2.3	
I.4.2.3	I.4.2.3	(I) 4.2.3 (II)									I.4.2.3	
	I.4.2.3										I.4.2.3	I.4.2.4
											I.5.2.3	
											I.5.2.4	
II.3.2.3		II.3.2.3	II.3.2.3									
II.3.2.3		II.3.4.3										
		II.4.1.4				II.4.1.4						
II.4.2.3												
II.4.2.3												
II.4.2.3												
		II.4.2.4						II.4.2.4				
		II.4.2.4						II.4.3.4			II.4.3.3	
		II.4.2.4									II.5.2.3	
		II.4.2.4									II.5.3.4	

COMPARISON WITH OTHER DISTRICTS

Data from several other districts are given in Table II. The method of comparison is modeled after the mathematical statement of the quantitative classification.[1] However, instead of using different bases for distinguishing rocks of the different classes, the plan in Table II is to use the same criteria for all rocks, making the figures strictly comparable through the whole table. The first term is the class (I to V) in the quantitative system. The second expresses, by groups (1 to 9), the ratios of quartz to feldspar, or lenads to feldspar. The third and fourth terms similarly express the ratio of alkalies to the lime of salic minerals, and the ratio of potash to soda, in molecular terms. These are the figures given below the norms in Table I of analyses of the Duluth lopolith.

Scarcity of intermediate rocks.—The impression obtained from the Duluth series is carried out in the others. There are few intermediate rocks in any of the districts. The samples contrast almost as sharply as at Duluth, though none seem to have as complete a series of analyses. The main rocks of the associated sequences are members of the gabbro family and granites. One rock collected by Daly in the Purcell sills is really intermediate, and this is a rock which was carefully selected with the idea of showing its transitional nature. Probably the Swedish monzonite and some syenites of the Adirondacks are also intermediate, but the papers describing them are not very definite as to their occurrence and relation. Even if the proof of gradational types is clear, as it is at Duluth, the data may well be taken as evidence that intermediate rock is less abundant than the several types on either side of the break. The sharpness of separation of types in the field has often been noted in regions of differentiated rocks.[2] To be sure it may be argued that a collector would choose clear types rather than a mixed indefinite specimen, but the facts at Duluth argue against any such condition. Here a good series showing variations of gabbro is available; but no series connects the several gabbros with the red rock; and, as

[1] Whitman Cross, J. P. Iddings, L. V. Pirsson, and H. S. Washington, *Quantitative Classification of Igneous Rocks*. University of Chicago Press, 1903.

[2] L. V. Pirsson and W. N. Rice, "The Geology of the Tripyramid Mountain," *Am. Jour. Sci.*, XXXI, 291.

said before, some were selected with the expressed intention of showing what the intermediate rocks are like.

In several large igneous bodies one of the differentiates has assumed intrusive relations to the others. In such cases it might be assumed that the disturbance is responsible for the abrupt change from one extreme to another; possibly the large amount of intermediate rock required by theory has been eroded, or is concealed in depth. Such arguments may apply to batholiths, but not to an intrusion with a floor, especially if it is as well exposed as at Duluth. Granted that there is a lack of intermediate rock at Duluth, the corresponding lack elsewhere indicates that intermediate rocks were never formed in any large quantity.

An argument for immiscible separation.—If this apparent break in the series is as normal and characteristic as it appears from the table, it gives a rather different impression from the simple sequence that has been suggested for the results of differentiation. Some modification or restatement of the outline of crystallization differentiation may bring it into closer accord with known series, but the clear impression from the series here tabulated is that two processes have been at work either successively or simultaneously.

If crystallization differentiation produced the banded gabbro, with differentiates ranging from peridotite and iron ore to anorthosite, what other processes can be conceived which might yield the red-rock differentiate? It cannot be that one is a regional and the other a local variation, for it is all in the same chamber. It is very likely to be a contrast between wet and dry. The first type of differentiation occurs in the presence of a very small amount of water (though biotite occurs even in the gabbro); and if the crystallization results in a concentration of water in the mother liquor, a point may be reached where the water has an effect not known in the earlier stages. Even in this case it is not clear why the water concentrating gradually would not yield a series of intermediate rocks in considerable volume.

The abruptness of the gradation leads almost conclusively to the idea of a separation of an immiscible liquid. This would be favored by the increased amount of water. Water was certainly abundant, as is indicated by numerous miarolitic cavities in the

red rock. It seems doubtful if any other process than the separation of immiscible fractions could operate with the separation of crystals to give such a distinct differentiate.

SUMMARY

The rocks of the Duluth gabbro lopolith are found to fall naturally into two series, one related to the gabbro family, the other more closely to the granites. Intermediate types are rare, though in the field the gradation between types is visibly complete. The abruptness of the separation in the field as well as in the arrangements on the basis of laboratory data indicates that the process involved in the separation of granite and gabbro was of a different nature from the more easily understood process by which a variety of phases developed in the gabbro. The several modifications of the gabbro probably resulted from a differentiation by crystallization during convection, aided by a slight amount of settling of crystals. Before the solidification was complete the granitic magma must have separated from the gabbro, probably by some other process, for the process giving variety to the gabbro seemed to produce no modification in it approaching the granite. The evidence is strong that differentiation of two sorts may occur in a single magma chamber. If crystallization and settling and convection are involved in the main process, it is interesting to suggest other possibilities for the other process. The difference may be due largely to a difference in the concentration of water, but the field and laboratory studies both strongly suggest an immiscible separation of the red rock from the gabbro.

November, 1918

POST-GLACIAL MOLLUSCA FROM THE MARLS OF CENTRAL ILLINOIS[1]

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The study of the biota contained in marl beds, and in other deposits lying upon the till of the late Wisconsin ice sheet, has added greatly to our knowledge of the post-glacial distribution of many mollusks and other animals, and has often provided data bearing on the changes of climate which have occurred during the interval between the retreat of the Wisconsin ice and the present time. The material that forms the basis for the present contribution adds to our knowledge concerning the post-glacial distribution of a few lacustrine and fluviatile forms of mollusks.

My thanks are due Dr. T. E. Savage, of the University of Illinois, for the opportunity of examining the material as well as for stratigraphic data bearing upon the deposit containing the collections; Dr. V. Sterki and Dr. Bryant Walker for the examination of critical material; and Professor Frank Smith for assistance in collecting material from the vicinity of Mahomet.

Marl deposits are extensively distributed in Michigan, Wisconsin, Maine, New Jersey, and other localities, being better known in the states named than elsewhere. Indiana, Ohio, and Illinois also contain marl beds of greater or less size, but these have not been as exhaustively studied for their biota. Marl deposits have rarely been reported from Illinois, a condition due to lack of observation rather than to absence from the territory.

The study of these marl deposits is of great interest and some value, a comparison of the marl fauna with the recent fauna usually showing a change from cold to temperate climate. Many species also indicate a more southward distribution during early post-glacial time. It is of importance that the marl deposits of the state

[1] *Contribution from the Museum of Natural History*, University of Illinois, No. 1.

of Illinois, of which there are doubtless many, should be examined carefully and their biota compared with the recent biota of the same region and with localities within the range of the different species. This is especially true as regards deposits of an interglacial character.

Three new marl deposits are discussed in the present paper, two near Mahomet, on the Sangamon River, and the third on the campus of the University of Illinois, in Urbana.

THE URBANA DEPOSITS

Excavations for the new greenhouse and for drains in the neighborhood show the following superposition of strata (section made by Dr. T. E. Savage):

Section of ditch through old pond

4.	Top soil or black clay without pebbles, grading down into number 3 below	20–24 inches
3.	Clay, dark above, becoming light gray and more calcareous below; containing numerous mollusks	18–20 inches
2.	Marl or limestone composed of more or less completely broken shells somewhat consolidated by cement of $CaCo_3$	8–12 inches
1.	Glacial till, pebbly, gray	6–12 inches

The depth of the section was about four feet.

The locality from which these fossils came is in a depression northeast of the new greenhouses, near the forest nursery. The topography at this place suggests a pond of considerable size and the molluscan life indicates quite a depth of water, at least in the center of the lake or pond. The glacial till here is the Champaign till sheet, and the body of water evidently stood in a kettle hole on the northern side of the Champaign moraine, which extends northwest and southeast through Champaign and Urbana (Leverett, 1899, pl. vi). This till sheet is of early Wisconsin age, and the relation of the marl to the till suggests that the pond or lake may have been inhabited by the mollusks when the late Wisconsin ice was resting at the Valparaiso moraine. The cemented character of the marl numbered 2 in the section also suggests considerable age. This lake or pond may have drained northeastward through the present Salt Fork Valley.

The fauna from these marls also indicates a cooler climate when the pond was occupied by the living mollusks, the southern limit of distribution of several of the species now being at a considerable distance north of this locality. Other extinct forms in this deposit were previously known only from the marls of Maine and Michigan. The distribution and other relations of the species from the Urbana deposits are shown in Table I; *x* indicates that no authentic Illinois records are known.

TABLE I

MOLLUSCAN DISTRIBUTION

Molluscan Species	Now Living in Urbana or Vicinity	Nearest Illinois Locality	Distance from Urbana in Miles	Fossil Only	Known from Marl of Michigan
Sphaerium rhomboideum		Menard Co.	80		
Sphaerium occidentale		Fulton Co.	95		*
Musculium rosaceum		*x*			
Musculium truncatum	#				*
Pisidium adamsi affine		Winnebago Co.	140		*
Pisidium contortum		*x*			*
Pisidium costatum		*x*		*	*
Pisidium tenuissimum calcareum		*x*		*	*
Pisidium variabile		Mason Co.	95		*
Pisidium vesiculare		*x*			*
Valvata sincera		*x*			*
Valvata tricarinata		Mason Co.	95		*
Physa gyrina	#				*
Physa sayii		Peoria Co.	81		
Planorbis trivolvis	#				*
Planorbis parvus urbanensis				*	
Planorbis altissimus				*	
Galba caperata	#				*
Galba obrussa decampi		Lake Co.	140		*
Galba reflexa		McLean Co.	48		*

An analysis of this table brings out several interesting features, as noted below:

Species now living in same territory	4
Species now living in same latitude	10
Species not now living in state (not yet reported)	8
Extinct species	4
Percentage of species also known from marl beds of Michigan	75 per cent
Percentage of marl fauna now living in Illinois	70 per cent
Percentage of marl fauna now living in vicinity of Urbana	20 per cent

It would be of great interest to compare other marl faunas of Illinois with the one herein described. It is quite probable that the new species, as well as the species now showing a more southward distribution in Pleistocene time, will also occur in other marl deposits of the state.

The collections are in the Museum of Natural History of the University of Illinois, and are included in numbers Z10755 to Z10803, inclusive.

ANNOTATED LIST OF SPECIES

SPHAERIIDAE

Sphaerium rhomboideum Prime

A portion of one right valve was the only evidence of the presence of this finger-nail clam, which is common, living in the northern part of the state.

Sphaerium occidentale Prime

One valve, apparently of this species, was observed by Dr. Sterki with a lot of Pisidia. It is a common species of the swales and small ponds in the northern half of the state.

Musculium truncatum (Linsley)

Rather plentiful. A number of specimens differ from the typical form in being larger, with narrower, more elevated beaks, which are inclined forward. *Truncatum* is a common species in the northern part of Illinois. The beaks of all these Musculia are strongly calyculate.

Musculium cf *rosaceum* (Prime)

A single valve is referred doubtfully to this species by Dr. Sterki. A single record of this species from the state is given by Wolf (1870, p. 27) for Fulton County, but the identification is doubtful. There is no authentic record from Illinois as far as known to me.

Pisidium tenuissimum calcareum Sterki

This fossil *Pisidium* is the most abundant mollusk in the marl bed under discussion, showing considerable variation. It has been previously known from the marls of Maine and Michigan, and its presence so far south of its hitherto recorded distribution is of great interest and indicates clearly a colder climate in early post-glacial time.

Pisidium costatum Sterki

Next to *Pisidium tenuissimum calcareum* this species is the most abundant mollusk in the collection. Of this species Dr. Sterki says, "For years I thought it might be a form of *Pisidium medianum*, but rather different; this find appears rather to vindicate it." It has not been observed among recent Pisidia and was previously known only from marl deposits in Michigan and Maine. With the previous species this southward distribution indicates a climatic change.

Pisidium vesiculare Sterki

A few rather small but characteristic specimens occur in the collection. This species is not known from Illinois as a living mollusk. It has been observed in the marls of Michigan.

Pisidium variabile Prime

One valve of this abundant species was found in the collection. It is a common species in the northern part of Illinois, both fossil and living, and it is strange that only a trace of its presence has been left in the bed at Urbana.

Pisidium adamsi affine Sterki

A single valve of a juvenile individual occurred with other Pisidia. It is known only from Winnebago County (collected by A. A. Hinkley).

VALVATIDAE

Valvata tricarinata (Say)

Not common. The individuals are sharply tricarinate, though the majority are immature. This species is a common mollusk in the ponds, lakes, and streams of the northern part of the state.

Valvata sincera (Say)

This valvata is quite common in the deposit. These are the first authentic specimens of *sincera* from an Illinois locality, specimens hitherto identified as *sincera* proving, upon examination, to be *lewisii* (see Baker, 1806, p. 91). The Urbana specimens of *sincera* were referred to Dr. Bryant Walker, who declared them to be quite typical of the species. This record indicates a wider southward distribution in early post-glacial time.

PHYSIDAE

Physa sayii Tappan?

A single immature shell is referred doubtfully to this species. It has the characteristic shape of a half-grown *sayii* and is covered with heavy impressed spiral lines. The individual has $4\frac{1}{2}$ whorls and is 12 mm. long. *Sayii* is a common species in northern Illinois and the states to the north.

Physa gyrina Say

The shells of this protean species occur in abundance in the marl deposit; the greater number of individuals, however, are immature, only about 3 per cent being fully mature. The largest specimen has 6 whorls and measures 26 mm. in length. *Gyrina* is distributed quite generally over the state and in the states north of Illinois.

PLANORBIDAE

Planorbis trivolvis Say

Not common in the marl deposit and the majority of individuals are immature. *Trivolvis* is a very common species in Illinois and adjacent states.

Planorbis parvus urbanensis Baker, n. var.[1]

This new form of *Planorbis parvus* occurred sparingly in the marl deposits and was apparently not as abundant in the post-glacial pond as the typical *parvus* usually is in ponds of a similar character. Typical *parvus* occurs living in the vicinity of Urbana.

Planorbis altissimus Baker, n. sp.[1]

This new species of *Planorbis* is represented by a few adult individuals and a number of young and immature specimens. It was apparently not as common as the variety of *parvus* listed above.

LYMNAEIDAE

Galba reflexa (Say)

This Lymnaeid occurs plentifully in the marl deposit and is very abundant and variable; the majority of individuals, however, are young or immature. *Reflexa* is commonly distributed over the greater part of Illinois.

[1] The new *Planorbes* will be described in the current number of the *Nautilus*.

Galba caperata (Say)

Caperata is abundantly distributed over the northern half of Illinois. The marl specimens are numerous, quite typical, and mostly mature.

Galba obrussa decampi (Streng)

This characteristic marl fossil is common in the Urbana marl deposit. The specimens show some peculiarities of interest. The whorls are very heavily shouldered, the sutures almost channeled, and the aperture is separated from the body whorl by a deep channel, causing the inner and outer lips to become continuous and the aperture to become auriform. There is some variation in the height of the spire and in the relative width of the shell. The collection contains both adult and young shells.

The Urbana shells give the most southern record for the distribution of the species; the only recent records from the state are in Lake and McHenry counties, and the only fossil record from post-glacial deposits is near Chicago. It is known living from a number of localities in Michigan, and from Maine, New York, and Michigan in marl beds (Baker, 1911, pp. 290–91, pl. 32, figs. 15–22). It is apparently a Pleistocene species that is dying out, being characteristic of the cold climate immediately following the retreat of the ice.

SANGAMON RIVER, NEAR MAHOMET

The mollusks from this locality occur in a sand stratum four feet below the surface. The fauna is distinctively of a fluviatile character and not of pond character, as is the case with the Urbana marl fauna. The species obtained by Dr. Savage are listed below:

UNIONIDAE

Fragments of a river mussel.

SPHAERIIDAE

Sphaerium solidulum (Prime)

Apparently rare. Found throughout the state.

Pisidium compressum Prime

A half-valve of this common Illinois species was found. It evidently drifted from a more favorable habitat.

VIVIPARIDAE

Ambloxis integra (DeKay)

A post-embryonic individual and two half-grown individuals occurred in the collection. It is a common *Campelona* (=*Ambloxis*) in Illinois.

VALVATIDAE

Valvata tricarinata (Say)

Apparently a rare species in this deposit.

AMNICOLIDAE

Amnicola limosa porata (Say)

One broken shell of this common *Amnicola* was noted in the collection.

PLEUROCERIDAE

Pleurocera elevatum (Say)

This common river snail is very abundant in these deposits and includes the typical form together with individuals showing spiral lines on the base of the shell, indicating a tendency to vary toward the race known as *lewisii*. In some individuals the growth lines near the aperture are raised to form costae. All ages are represented, and the young are strongly carinate. *Elevatum* is distributed throughout the state.

PLANORBIDAE

Planorbis antrosus Conrad (=*bicarinatus* Say)

Three specimens of this widely distributed species were observed in the collection. The single adult individual is small for the species.

ENDODONTIDAE

Pyramidula solitaria (Say)

A single broken shell of this species of land snail was found with the fresh-water species, evidently a stray individual which had fallen or been washed into the stream.

SANGAMON RIVER, BELOW MAHOMET

About three-quarters of a mile below Mahomet, on the north bank of the Sangamon River at the first bend below the second bridge, a sand stratum occurs in a section of the river bank on the old flood plain. The stratum is about 2 inches in thickness and lies from 8 to 12 inches below the surface of the river terrace and about 5 feet above the level of the river, the latter being rather high for the season (July). The deposit can be traced for over a hundred feet in the bank. Its extent in the terrace could not be ascertained, but it is apparently considerable. At one place it disappeared beneath a large tree stump over two feet in diameter, indicating that the deposit antedated the present forest. The terrace here appears to be above the influence of the highest water, and it is evident that the deposit is post-glacial and was laid down before the Sangamon had cut its bed to the present depth. It possibly represents the flood plain of an earlier Sangamon.

It will be noted that this deposit is at a higher level than the one examined by Dr. Savage, and is probably younger. Of the species obtained from the higher level, 8 are different from those collected by Savage, and 4 species are included in the Savage collection that are not in the Baker collection. *Pleurocera elevatum* occurs in both collections and is still living in the Sangamon River. In both fossil deposits it is very variable in the degree of spiral ornamentation, varying, perhaps, more than the recent shells of the Sangamon. *Ambloxis integrum* is fairly common at the higher level deposit but rarer at the level from which Dr. Savage collected his specimens. This species lives in the Sangamon in large numbers but has not as long a spire as the fossil individuals.

The surface of the flood plain of the Sangamon River near the first bridge below Mahomet is covered with dead, bleached shells of mollusks, of the same species, mostly, as those found in the deposit examined lower down the river, but they are mixed more or less with recent shells from the river and their age and stratigraphic relation cannot be definitely determined. No deposit comparable to that found in the bend of the river below Mahomet was observed here, though the river bank was carefully examined for a

considerable distance. It is not safe to list such material, and it has therefore been ignored.

The list of mollusks obtained from the high-level deposit is as follows:

SPHAERIIDAE

Sphaerium sulcatum (Lamarck)

Rare, only a half-valve was found.

Sphaerium stamineum (Conrad)

Not abundant, 7 valves included in the collection.

Sphaerium solidulum (Prime)

A half-valve is doubtfully referred to this species by Dr. Sterki. It is broken, but is apparently the same as the shells from the lower deposit referred to this species by Sterki.

Pisidium virginicum (Gmelin)

A half-valve of this large *Pisidium* was found. It is common as a Pleistocene fossil and as a recent mollusk in Illinois.

Pisidium compressum illinoisense Sterki

Three valves. The presence of this recently described Pisidium in this Pleistocene deposit is of interest. It lives in a reservoir and pond in Washington County, near Dubois, and in Sheller Lake, Jefferson County, in great numbers, obtained by the veteran Illinois collector, Mr. A. A. Hinkley. Of the species Sterki says (1916, p. 448), "All are of the same shape, differing somewhat in size and color, but remarkably uniform in each habitat. It is a peculiar form, having almost the significance of a species." Typical *compressum* was the only form of this genus found in the material collected by Dr. Savage.

VIVIPARIDAE

Ambloxis integra (DeKay)[1]

This large snail occurs in the deposit in considerable numbers; the majority of the individuals, however, are young or half-grown. The adult shells are unlike any figured in the monographs, resembling most nearly Haldeman's figure 2 of his monograph, but with

[1] See Pilsbry, *Nautilus*, XXX, pp. 109–14, 1917, for the reasons for the change of generic name from *Campeloma*.

a longer spire and deeper sutures. There are seven full whorls in the largest fossil specimen, which measures as follows: Length, 40; breadth, 22; aperture length, 20; breadth, 12 mm.

Integra is widely distributed in Illinois but has been confounded with *subsolida* and *decisa*, from both of which it differs notably.

VALVATIDAE

Valvata bicarinata Lea

Not common.

AMNICOLIDAE

Amnicola limosa (Say)

Two shells of this species were observed in the loose sand taken from the aperture of Ambloxis.

PLEUROCERIDAE

Pleurocera elevatum (Say)

As in the deposit examined by Dr. Savage, this species is the dominant mollusk in the deposits examined by the writer, and the shells exhibit the same range of variation as do those from the lower stratum. Several individuals are smooth without indication of spiral lination and every degree of ornamentation is represented to shells with a heavy, keel-like carina on the periphery. This species is abundant, living in the Sangamon River, where it is equally variable.

PLANORBIDAE

Planorbis antrosus Conrad

Rather common, but the individuals are smaller than normal.

Planorbis campanulatus Say

One adult shell of this species was found in the collection.

ENDODONTIDAE

Pyramidula alternata (Say)

Several shells of this common land mollusk were collected from the deposit, indicating that this wood snail has lived in this vicinity for a long time. It was not found in the lower deposit but a related species, *Pyramidula solitaria*, occurred.

TABLE II

RELATION OF MOLLUSCAN SPECIES TO THE TWO DEPOSITS ON THE SANGAMON RIVER

	Savage	Baker	Now Living in River*
Sphaerium sulcatum		x	
Sphaerium striatinum		x	
Sphaerium solidulum	x	x	
Pisidium virginicum		x	
Pisidium compressum	x		
Pisidium compressum illinoisense		x	
Ambloxis integra	x	x	x
Valvata tricarinata	x		
Valvata bicarinata		x	
Amnicola limosa		x	
Amnicola limosa porata	x		
Pleurocera elevatum	x	x	x
Planorbis antrosus	x	x	
Planorbis campanulatus		x	
Pyramidula alternata		x	x
Pyramidula solitaria	x		

* Some of these species may be found living in the Sangamon or its vicinity.

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